

**Physiological and psychological contributions to on-sight rock  
climbing, and the haemodynamic responses to sustained  
and intermittent contractions**

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A thesis  
submitted in partial fulfilment  
of the requirements for the Degree of  
Doctorate of Philosophy

at  
University of Canterbury  
by  
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University of Canterbury  
2013

## Abstract

Rock climbing is a multi-dimensional sport encompassing physiological, psychological, bio-mechanical and skill components. Interpretation of data in current investigations is limited by the lack of knowledge regarding the extent of the potential interaction of pre-climb anxieties with the physiological responses during an ascent. This thesis attempts to delineate the psychological and physiological contributions of on-sight top rope and lead climbing in multiple ability groups of rock climbers. Furthermore, the thesis goes on to gain an understanding of the de-oxygenation and re-oxygenation profiles in two forearm flexors during sustained and intermittent contractions-to-failure, as well as during the subsequent recovery period.

In study one, intermediate, advanced and elite rock climbers were asked to on-sight a route at the top of their respective best self-reported on-sight grade. There were no ability group or ascent style differences for any pre-climb measures of anxiety. However, elite rock climbers had significantly higher oxygen consumption, heart rate (HR) and cortisol (physiological component) responses compared to lower ability groups. Furthermore, the elite climbers spent a significantly greater percentage of their static time resting during the ascent compared to all lower ability groups. As there appears to be no differences in the anxiety based interaction with the physiological response, study one suggests that ability group and ascent style differences may be attributed mainly to the changes in the physical demands of the route. Furthermore, it would appear the higher level rock climbers may have a greater reliance on the aerobic metabolism during an on-sight ascent.

Study two investigated the haemodynamic responses to sustained and intermittent handgrip contractions which are seen during rock climbing ascents. Intermediate, advanced and elite climbers as well as a control group were asked to perform sustained and intermittent contractions (10s) at 40% of maximal volitional capacity until exhaustion. Oxygen saturation, blood flow (BF) and HR were measured pre, during and post contractions. Elite and advanced climbers were able to de-oxygenate both the flexor digitorum profundus and the flexor carpi radialis significantly more than the intermediate climbers, and the control group. During the intermittent test to failure, *relative* re-oxygenation during the rest period (3s) (re-oxygenation which takes into account the amount of de-oxygenation during the previous contraction), may be an important determinant of the force time integral. During the intermittent test, the increase in  $\Delta$  BF, release HR and  $\Delta$  HR during the rest periods suggest that vessel occlusion in elite and advanced rock climbers may not be as prominent as previously speculated upon. Furthermore, elite rock climbers appear to have a significantly faster time to half recovery after both sustained and intermittent contractions-to-failure.

In conclusion, it would appear that the psychological responses assessed pre on-sight rock climbing may not be different between ability groups or ascent styles. Instead, ability group differences may be due to physiological adaptations caused in part by the significantly greater amount of training. Furthermore, elite rock climbers appear to be able to de-oxygenate and re-oxygenate faster and to a greater extent than lower ability level climbers due to an increased  $\Delta$  BF and  $\Delta$  HR during intermittent rest periods, as well as post-exercise. Further investigation focusing on aerobic/anaerobic contribution, determination of capillary density and muscle fiber type would aid in gaining a greater understanding of rock climbing performance.

**Keywords:**

**Rock climbing, psychophysiology, oxygen consumption, cortisol response, muscle oxygenation, blood flow, haemodynamics, forearm flexors**

## Acknowledgements

On a professional level I would first and foremost like to thank my supervisor Dr Nick Draper for his invaluable support and encouragement, for always being there to reel me back down to reality and always having an open door. Your patience and enthusiasm for my studies have spurred me on through some tough times. Furthermore, I would like thank you for finding me funding in the form of continual teaching at the University throughout the entirety of my PhD process. Nick, without your help none of this would have been possible.

Dr Lee Stoner, without your help, support, and guidance I would never have been able to complete this piece of work. Thank you for the numerous weeks that you spent away from your home and your patient and understanding wife Kristina. Your help and expertise in collecting blood flow data in a tough and challenging setting was invaluable.

Dr David Winter, thank you for all your advice and timely proof reading, and for battling through my addiction to semi colons; that one is for you.

I am very grateful to Dr Carl Scarrott for being a statistician who has an incredible ability to make statistics both easy to understand, and enjoyable. Your help in strengthening my knowledge and the analysis of my PhD has been invaluable.

Drs John Lewis and Peter Elder in the Steroid Laboratory at the Canterbury Health Laboratories, thank you for your generosity, kindness and patience in teaching me how to analyse cortisol using ELISA techniques.

On a personal level, I would like to thank my family and friends for the unbelievable amount of support you have given me over the years preceding this event. To my grandad who has been such an inspiration throughout my life, I hope one day I may be as clever as you are. To my gran for the support and encouragement in whatever I choose to do in life. To my brother for being an inspiration and spurring me on through hard times.

Finally I would like to acknowledge the most important people in my life, my mum and dad. Without your help, support, encouragement, guidance and love in every aspect of my life I would not be at this moment, this is dedicated to you.



This thesis is dedicated to the memory of

Jamie Vinton-Boot

June 24<sup>th</sup> 1983 – August 12<sup>th</sup> 2013

May you be at peace amongst the mountains you loved so much

Me te aroha tino nui

## Publications and Presentations

**Preliminary studies conducted to improve the methods for research conducted within this thesis:** Publications where I was a member of the research team.

Dickson, T., **Fryer, S.**, Draper, N., Winter, D., Ellis, G. & Hamlin, M. (2012) Comparison of plasma cortisol sampling sites for rock climbing. *Journal of Sports Medicine and Physical Fitness*, 52(6), 688-695.

**Fryer, S.**, Draper, N., Dickson, T., Blackwell, G., Winter, D., & Ellis, G. (2011). Comparison of lactate sampling sites for rock climbing. *International Journal of Sports Medicine*, 32, 428-432.

Draper, N., Couceiro, J., **Fryer, S.**, Dickson, T., Winter, D., Ellis, G., et al. (2011). Reporting climbing grades and grouping categories for rock climbing. *Isokinetics and Exercise Science*, 19(4), 1-8.

Draper, N., Dickson, T., Blackwell, G., **Fryer, S.**, Priestley, S., Winter, D. & Ellis, G. (2011). Self-reported ability assessment in rock climbing, *Journal of Sports Sciences*, 29(8), 1-8.

**Preliminary studies conducted to improve the methods for research conducted within this thesis:** Publications where I was a leading member of the research team.

**Fryer, S.**, Dickson, T., Hillier, S., Draper, N., Stoner, L., Lucero, A. & Witter, T. (2013). A comparison of salivary, capillary, venous and cortisol sampling following intense maximal exercise. *International Journal of Physiology in Sport*, (Under Review).

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### Publications arising from study one

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**Fryer, S.** Stoner, L. Draper, N. Scarott, C. & Dickson, T. (2013). Muscle tissue oxygenation dynamics during a sustained contraction in different ability rock climbers. *Poster presentation at British Association of Sport and Exercise Scientists 3<sup>rd</sup> – 5<sup>th</sup> September 2013, Lancashire United Kingdom. (Accepted)*

**Fryer, S.** Dickson, T. Draper, N. Blackwell, G and Stoner, L. (2012). The effect of ability and technique on  $\dot{V}O_2$  & heart rate drift in rock climbing. *Poster presentation at American College of Sports Medicine Conference, May 29<sup>th</sup> – June 2<sup>nd</sup> 2012, San Francisco, California, USA.*

Stoner, L. **Fryer, S.** Dickson, T. Hillier, S. and Draper, N. (2012). Capillary and Salivary Cortisol Samples Accurately Reflect Venous Cortisol Following Intense Exercise. *Poster presentation at American College of Sports Medicine Conference, May 29<sup>th</sup> – June 2<sup>nd</sup> 2012, San Francisco, California, USA.*

**Fryer, S.**, Dickson, T., Draper, N., Blackwell, G & Stoner, L. (2011). Psychological and performance aspects of on-sight rock climbing in intermediate, advanced and elite climbers. *International Rock Climbing Research Congress, November 28<sup>th</sup> – December 2<sup>nd</sup> 2011, University of Canterbury, New Zealand. [Oral, Keynote]*

Dickson, T., **Fryer, S.**, Blackwell, G., Draper, N and Stoner, L. (2011) Psychophysiological demands of rock climbing for elite level climbers during on-sight ascents. *International Rock Climbing Research Congress, November 28<sup>th</sup> - December 2<sup>nd</sup> 2011, University of Canterbury, New Zealand. [Oral, Keynote]*

Draper, N., Shearman, J., Dickson, T., **Fryer, S.**, Blackwell, G., Winter, D., Ellis, G and Hamlin., M. (2011) *The role of psychophysiological interaction on fatigue in rock climbing.* Poster presentation at UK: BASES Conference, 6 - 8th September 2011. In *Journal of Sports Science.*

## **Additional publications completed during PhD process**

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# Definition of Terms

## *General Rock Climbing Terms*

**Abseil** - A controlled descent down either a single or double rope, usually completed in retreat after ascending a rock face.

**Adjective grading system (British)** – The part of the British grading system, which denotes the severity of a route (traditional only) for the *lead* climber. The system starts at Moderate (M) and currently ends at Extreme 12 (E12).

**Arête** – A ridge like feature or a outward facing corner on a steep rock face.

**Belaying** – A process carried out by the person at the bottom or top of a route. The rope passes through a device on the *seconds* harness. This device when activated stops the rope being *payed out* if the climber were to fall.

**Bolt** – Expansion bolt often referred to as a *running belay*. A bolt is used in *sport climbing* to protect the *leader* if they fell. The leader generally clips the bolt with a *karabiner* or *quickdraw*.

**Chimney** – A crack in the rock which is wide enough to fit the entire body in.

**Chock** – A wedge or hexagonal shaped piece of metal that is attached to a *wire* or *sling*. Often referred to as a *running belay*. These are placed into cracks in rock to protect the climber if they were to fall.

**Clean/flash** – When a route has been completely climbed without any falls or weighting of the rope.

**Clipping** – The action performed when the climber attaches their rope to a *running belay*.

**Crag** – A word used throughout the world to describe an outdoor rock face, which has several routes on it.

**Crux** – The hardest section of a route.

**Exposure** – The increasing sense of height as a climb ascends. This is often felt more on steep open rock faces. The feeling a climber gets can be debilitating.

**Ewbank** – The grading system named and developed by John Ewbank in the 1960s is used in New Zealand, Australia and South Africa. It is open ended starting at 1 (a walk) and currently ends at 36.

**Gully** – A deep ditch or ravine which is cut in the earth.

**Karabiner** – A metal snap link that links two things together such as the climber to a *rope*, *protection* to the *rope* and *belay plate* to *harness*.



**Nut** – A small metal block with a wire on it. It is placed into cracks in the rock face as a *running belay* to protect the *leader* in a fall.

**On-sight** – A route that is attempted with no prior knowledge or inspection whatsoever.

**Pitch** – A stretch of rock face between two belay positions or the ground and the top of the climb.

**Piton** – A metal peg with a hole in the end for attachment of a *karabiner*. A *piton* is usually hammered into a small crack in a rock face before *clipping* the rope to it via a *karabiner*. Pitons are used for *protection* (*running belays*) whilst climbing a route.

**Problem** – A specific climb or part of a climb, usually used to describe a *bouldering* route.

**Protection** – Any form of *running belay* which attaches to the rock to help protect the climber if they fell, such as: *piton*, *bolt*, *chock* or *sling*.

**Pumped** – When a climber is at their maximal physical limit and has a burning sensation in the forearms to the point of pain.

**Quickdraw** – A small piece of webbing with a *karabiner* attached to each end. It is generally used to connect *protection* (*bolt/wire/nut* etc) in the crack to the rope of the *leader*.

**Red-point** – When a climber has practised a specific route over and over again until it has been ascended *cleanly* with no falls or weighting of the rope.

**Run Out** – The distance between a piece of *protection* (*running belay*) and the climber. A long *run out* can often be very dangerous to the climber, as they would travel a great distance if they fell.

**Running Belay** – A *bolt*, *chock*, *sling* or any form of *protection* on a route, which attaches the climber to the wall.

**Sling** – A loop of webbing which can be used to attach several pieces of climbing gear together or can be looped over a rock to protect the *leader* from a fall.

**Slab** – A section of rock which is less than vertical.

**Technical grade (British)** – The part of the British grading system, which purely denotes the technical difficulty of a route. The technical grading system is also used in the French grading system.

**Treadwall** – A rotating climbing wall that moves by the application of body weight or motor, may also be referred to as a ‘climbing ergometer’. A vertical treadmill with modular holds attached that can be manipulated to afford differing angles and speeds of ascent.

**YDS (Yosemite Decimal System)** – The grading system was developed by the Sierra Club in the 1930's for walkers in the Sierra Nevada. The rock climbing section was added in the 1950's in California.

### ***Climbing Movements, Holds and Grips***

**Closed crimp** – When a climber pulls a hold with the distal parts of their fingers and their thumb is wrapped over the top of the fingertips.

**Crimp** – When a climber grips a hold using almost entirely finger strength from the distal parts of the fingers.

**Dyno** – A term used to describe a dynamic move in climbing such as jumping from one hold to the next.

**Edging** – When a climber places either the inside or outside edge of their shoe on to hold.

**Jug** – A hold in which the climber can grab with ease, almost the full length of the fingers can fit over or in to the hold. These are usually found on beginner routes and easy climbs.

**Match** – When both hands are placed onto either a foot or hand hold.

**Open crimp** – Similar to a *closed crimp* however, the thumb is not wrapped over the top of the fingertips. The hand is in an open position on the hold.

**Twist lock** – A move used with either the fingers stacked on top of each other, or the entire hand. The digits are placed horizontally into a crack before being twisted to increase surface area. This movement jams the digits and allows the climber to pull up on them.

**Pinch** – When a climber must use their thumb and fingers to squeeze the sides of a hold.

**Side Pull** – A technique used by climbers where they have to pull in a sideways direction on a hold in order to gain upward movement of the body.

**Sloper** – The climber must grab a hold with an open hand (like palming a football), the hold usually has no difference in surface texture making it difficult to hold.

**Static move** – A term used to describe the slow, steady and balanced nature of a climbing move. No fast dynamic movement (*dyno*) is performed.

**Bridge** – A climber uses two walls of close proximity, to oppose forces and ascend a section of a route.

## ***Climbing Disciplines***

***Artificial (aid) climbing*** – The climber pulls directly onto a piece of *protection* such as a *block*, *bolt*, *chock*, or *sling* rather than climbing the rock.

***Bouldering*** – Climbing relatively low to the ground without a rope for protection. Usually a crash pad is placed below the *problem* as a form of protection.

***Free climbing*** – Climbing a rock face without weighting *protection*. These pieces of *protection* are not used in any way to aid the upward progress of the climber.

***Leader (Leading)*** – The first person to climb a *pitch*. The *leader* is potentially exposed to significant falls depending on where the *running belays* are placed.

***Seconding*** – Generally considered the *second* person to climb a *pitch*, following up the *leader*. The *second* is attached to a rope from the top, which prevents a fall and is considered much safer than *leading*.

***Soloing*** – Climbing a route with no protection at all. If the climber falls they are likely to severely injure themselves or die.

***Sport climbing*** – Specially prepared routes with pre placed bolts every few meters. It is relatively rare in the UK but common all over Europe and the US.

***Traditional climbing*** – Climbing a *pitch* or more, using only removable forms of *protection (running belays)* such as *wires* and *nuts* NOT *bolts* as seen in *sport climbing*. The *leader* places these *running belays* in the rock to protect them if they fall; the *second* removes them as they climb up. This form of climbing is considered far more dangerous than *sport climbing*, as the *running belays* are more likely to fail in a fall.

***Top rope*** – Climbing with a rope attached from above.

***Leading on a top rope*** – Climbing with a rope attached from above, whilst performing the physical task of lead climbing. A technique used for teaching lead climbing with the safety of having a top rope.

# List of Abbreviations

## *Scientific abbreviations*

1RM .....	One rep max
ACTH .....	Adrenocorticotrophic hormone
ATP-PCr .....	Adenosine triphosphate – Phosphocreatine
ATP .....	Adenosine triphosphate
ADP .....	Adenosine diphosphate
AMP.....	Adenosine monophosphate
BF .....	Blood flow
BLa .....	Blood lactate
Bts·min <sup>-1</sup> .....	Beats per minute
CBG .....	Corticosteriod binding globulin
cm·s .....	Centimetre per second
CNS .....	Central nervous system
CSAI-2R .....	Competitive State Anxiety Inventory (Revised)
EE .....	Energy expenditure
ELISA .....	Enzyme-linked immunosorbent assay
EMG .....	Electromyogram
eNOS .....	Endothelium constitutive nitric oxide synthase
FCR .....	Flexor carpi radialis
FDP .....	Flexor digitorum profundus
FDS .....	Flexor digitorum superficialis
FTI .....	Force time integral
HCl .....	Hydrochloric acid
HGD .....	Handgrip dynamometry
HPA .....	Hypothalamic-pituitary-adrenal axis
HR.....	Heart rate
HRP .....	Horseradish peroxidase
IPAQ .....	International Physical Activity Questionnaire
Kcal·kg <sup>-1</sup> ·min <sup>-1</sup> .....	Kilocalorie per kilogram per minute
Kcal·min <sup>-1</sup> .....	Kilocalorie per minute
Kcal·m <sup>-1</sup> .....	Kilocalorie per metre
Kg .....	Kilogram
L·min <sup>-1</sup> .....	Litres per minute
mg·L .....	Milligrams per litre
MHz .....	Megahertz
mL .....	Millilitre
mL·kg <sup>-1</sup> ·min <sup>-1</sup> .....	Millilitres per kilogram per minute
mmol·L <sup>-1</sup> .....	Millimols per litre
mol .....	Molar
MVC .....	Maximal volitional capacity
N.....	Newton

NASA-TLX .....	National Aeronautics and Space Administration Task Load Index
N/kg .....	Newton divided by kilograms
ng .....	Nanogram
ng·mL .....	Nanograms per millilitre
nm .....	Nanometre
nmol·L .....	Nanomols per litre
NIRS .....	Near infrared spectroscopy
N x s .....	Newtons multiplied by seconds
O <sub>2</sub> .....	Oxygen
POMS .....	Profile of Mood States
RONS .....	Reactive oxygen nitrogen species
RPM .....	Revolutions per minute
TMB .....	Tetramethylbenzidine
$\dot{V} O_2$ .....	Volume of oxygen consumed
$\dot{V} O_{2peak}$ .....	Peak volume of oxygen consumed
W .....	Watts
$\dot{V} O_{2max}$ .....	Maximal oxygen consumption

### *Non – scientific abbreviations*

Adv .....	Advanced group
A&E .....	Accident and emergency
Aus .....	Australia
BMC .....	British Mountaineering Council
D .....	Difficult (climbing grade)
E .....	Extreme (climbing grade)
HS .....	Hard severe (climbing grade)
HVS .....	Hard very severe (climbing grade)
ICC .....	International Council for Climbing Competition
IFCS .....	International Federation of Sport Climbing
Int .....	Intermediate group
IOC .....	International Olympic Committee
LD .....	Lead climb
M .....	Moderate (climbing grade)
NA .....	Not applicable
NZ .....	New Zealand
OS .....	On-sight climb
RP .....	Red-point climb
TR .....	Top rope climb
UIAA .....	Union International des Associations d'Alpinism
UK .....	United Kingdom
USA .....	United States of America
V .....	Vermin scale (bouldering grading system)
VD .....	Very difficult (climbing grade)
YHA .....	Youth Hostel Association
TR .....	Top rope
LD .....	Lead

## **Introduction**

Rock climbing stemmed from mountaineering during the mid 19<sup>th</sup> Century, and the first official rock climb took place in the Lake District (UK) on Naples Needle in 1886. Nonetheless, it was not until the 1990's that rock climbing truly emerged as an internationally competitive sport. Rock climbing now encompasses numerous disciplines such as sport climbing, bouldering, traditional climbing and free soloing. On the 14<sup>th</sup> of July 2011 the International Olympic Committee (IOC) moved the discipline of 'sport rock climbing' to the short list for the 2020 Olympic Games. However, despite this recent acceptance by the IOC, and its growth in international competitiveness, there remains limited performance related research within the sport.

Although to a lesser extent than mainstream sports, the limited research in rock climbing has begun to increase within the last 20 years (Table 3.1). Research traditionally focused on accident occurrence (Foray et al., 1982; Schussman & Lutz, 1982), and injury incidence and prevention (Bannister & Foster, 1986; Bollen, 1988; Bowie, Hunt, & Allen 1988). However, as the sport became internationally competitive in the 1990's, a small body of research emerged which focused on anthropometric profiles and training guidelines. Unfortunately, these were limited to only a few peer reviewed journal articles (Shirer, 1990; Watts, Martin, & Durtschi, 1993a) and books (Gregory, 1989; Skinner & McMullen, 1993). Furthermore, much of the research presented had been conducted using non-climbing specific apparatus and therefore lacked specific relevance to the sport.

The slow growth of rock climbing research may be in part due to the nature of the sport imposing many methodological challenges, such as standardisation of international grading systems, route profiles and ascent styles. Furthermore, there may be important interactions between the psychological and physiological mechanisms during ascents. The only known studies which attempted to quantify these interactions have done so using intermediate level climbers only (Draper, Jones, Fryer, Hodgson, & Blackwell, 2008; Draper, Jones, Fryer, Hodgson, & Blackwell, 2010; Hodgson et al., 2009). The potential psychological interaction in all other ability groups has been merely speculated

upon within the literature. There remains a need to elucidate the psychological and physiological mechanisms which underpin the sport, in order to enhance both knowledge and physical performance. Furthermore, these measurements need to be methodologically sensitive to the dynamic nature of the sport.

### ***1.1.1 Thesis overview***

This thesis provides a historical overview of the evolution and growth of rock climbing, and its transition to a competitive sport. This will be followed by an in-depth review of rock climbing research from the earliest known studies to the most current. This thesis contributes to the literature by comparing ability group differences for: 1) the interaction between psychological and physiological responses seen during on-sight top rope and lead ascents, and 2) the haemodynamic responses of the forearm flexors during and after intermittent and sustained exercise. Therefore, the research body of the thesis is comprised of two main studies. Study one investigates (a) whether there were ability group and ascent style differences in pre-climb anxieties, and (b) the potential physiological differences between both ability groups and ascents styles, whilst on-sight climbing near or at a maximum performance grade. Study two investigates ability group differences in the haemodynamic responses during and after sustained and intermittent contractions-to-failure, within the flexor digitorum profundus (FDP) and the flexor carpi radialis (FCR) muscles.

Embodied within this thesis are publications formed from a small research team based at the University of Canterbury, New Zealand. My contributions to the aforementioned publications list (pages vi – xi) varies between each article, an overview of this contribution can be found in the Co-author forms (page 276 – 282).

### ***1.1.2 Significance of studies***

Assessments of the potential psychological and physiological interactions during on-sight rock climbing, as seen under competition conditions, are almost non-existent within the current literature. To date, previous studies have only reported data on intermediate rock climbers. When investigating multiple ability groups of climbers,

there has been no known research which attempts to determine the underpinning psychological and physiological contributions. It is hoped that a greater understanding of psychological nervous response in multiple ability groups, ascending on top rope and lead, would enable more accurate physiological conclusions to be drawn. The recognition of the physiological contributions in these groups led to an in-depth investigation into the haemodynamics of the forearm flexors, one of the most physiologically important aspects of a climber's performance. This clarity in the haemodynamic responses in different ability level rock climbers has helped to more clearly identify the determinants of elite level performances. Furthermore, this research has allowed for future investigations to assess potential training methods which target the physiological mechanisms associated with elite level performers.

### ***1.1.3 Purpose statement***

The purpose of study one was to determine whether there were ability group and ascent style differences in the psychological and physiological responses pre and post on-sight rock climbing at the top of a climber's self-reported ability level.

The purpose of study two was to ascertain whether there were ability group differences in the haemodynamic responses of the FDP and FCR during and after sustained and intermittent contractions-to-failure at 40% of maximal volitional contraction (MVC).



## Introduction to Rock Climbing

### 2.1 The history and development of climbing

The following subsections describe in detail the development of rock climbing, from its origins in mountaineering, to its evolution into a bold and competitive sport. Particular attention will be paid to the early foundations and developments of the climbing, the most notable ascents and conquests, and how ‘sport climbing’ became internationally competitive.

#### 2.1.1 *The early years*

The will to succeed in a modern day ‘hardest’ ascent is often driven by a substantial combination of intrinsic and extrinsic motivation. The will to be the best, an elite performer, whilst living to tell the tale, consumes the lives of top end professional climbers throughout the world. However, it was not always like this. The climbing community did not set out all those years ago to be the best, climb the hardest, and on-sight routes at the top of their physical and mental ability. Rock climbing was first discovered as an accessory and necessity to mountaineering, which at the time was not a sport in its own right. Furthermore, most mountaineers considered any such route, which involved the use of the hands to be foolish, dangerous, and an act of outright stupidity (Thompson, 2011).

To the impartial observer, Britain is a relatively flat country with little to no mountains. However, it is suggested that the British invented the sport of rock climbing, and for two distinct periods in time, the second half of the 19<sup>th</sup> Century and the latter part of the 20<sup>th</sup> Century, they led the world (Thompson, 2011). Prior to the 1850’s, mountains were ascended in the European Alps by monks, priests and scientists as a means of exploiting the land for its rare plant life, animals and mineral resources. Remarkably, during these early years nine major peaks were claimed: Mont Blanc (1786), the Grossglockner (1800), Monte Rosa (1801+), the Ortler (1808), Jungfrau (1811), Finsteraarhorn (1829), Wetterhorn (1844), Mont Pelvoux (1848) and Piz Bernina (1850). Unfortunately these

ascents, as remarkable as they were, failed to capture the spirit of the people and the activities did not coalesce into a 'sport' per se. However, all of this began to change in 1850 when the British arrived in the European Alps with the intention of ascending its high summits for reasons not of botany or science but for pleasure, and heightened social status (Unsworth, 1994). It was then that mountaineering entered into the 'Golden Age' of alpinism, and between 1854 and 1865 39 major peaks in the Alps were conquered, of which only eight were by non-British parties. It was during this intense period of mountaineering that the British were said to have invented the 'sport' of mountain climbing (Thompson, 2011).

### ***2.1.2 The foundation of mountain climbing***

It was Alfred Wills who is said to be both the founder of the sport of mountaineering, and the person who initiated the Golden Age of British exploration and mountain climbing, with his ascent of the Wetterhorn in 1854 (Thompson, 2011). Although the Wetterhorn had been ascended numerous times before (eight), it was the style in which Wills ascended, and the way he wrote of the endeavour in his later book *Wandering Amongst the High Alps* (Wills, 1856) which proclaimed him as the founder. The author refers to those who climb for science, botany and geology, yet he also talks of his ascent as one of a need for physical exercise and self-improvement (Wills, 1856). Furthermore, Wills suggested that it was the duty of any self-respecting English gentleman to undertake such adventures. Alfred Wills's ascent was classed as the beginning of the Golden Age. However, this seems unfair as the earlier publicised ascent of Mont Blanc in 1851 by Albert Smith was far more courageous (Thompson, 2011). Unfortunately, the soon to be Alpine Club (which formed in 1857) did not regard Smith as 'respectable', and Wills was unfairly given the founding honour.

From the mid 19<sup>th</sup> Century, upper-middle class professionals embarked on journeys to find routes of greater difficulty in every corner of the globe including the: Caucasus, Rockies, Andes and Himalaya. These explorations were embarked upon for many years, and even members of Will's family continued to seek thrills in mountainous explorations. This included his grandson Major Edward Norton, who led the 1924 Everest expedition (Unsworth, 1994). The theme of upper-middle class mountaineering ascents spread throughout the British class system like wild fire, growing vastly in

popularity. In 1857 the reverent S.W. King wrote of '*young Cantabs and Oxonians scampering over pass after pass, often with no other object than seeing who can venture into the most novel break-neck situations possible*' (Unsworth, 1994). In 1879 it was Queen Victoria's diamond jubilee, and as the empire grew the population of the UK grew with it, reaching approximately 40 million. It was John Stewart Mill who realised that the empire represented 'a vast outdoor relief for the British upper classes' (Morris, 1968). Even those who were left behind were obsessed with adventure. For many years the appeal for adventure appeared to have driven mountaineers in their search for personal fulfilment.

### **2.1.3    *The birth of British rock climbing***

After spending many seasons in the Alps, Leslie Stephen, a prolific scholarly mountain climber in the late 19<sup>th</sup> Century realised there were many unclimbed peaks to claim back at home. On his return journey in 1860 he spent several hours scrambling to make the first ascent of Pillar Rock (Cram, 1986). However, it was not until the 1870's that the British began to realise the full potential of crags in the UK as good preparation ground for harder ascents in Europe and elsewhere (Unsworth, 1994). Until this period, climbing was based on scrambling up gullies and hard walking, but gradually attention was turning to rocky ridges and shallow angled slabs. It was here that the 'birth' of rock climbing is said to have occurred in 1886, some 30 years after the Golden Age of alpine climbing had begun, and three years after the first expedition to the Himalaya. It is suggested the birth of rock climbing took place with the first documented ascent of Naples Needle (now graded Hard Very Difficult (HVD) in the Lake District 1886 (Cram, 1986; Hankinson, 1977; Thompson, 2011; Unsworth, 1994).

Although alpine climbing was still dominated by the upper class and the wealthy, rock climbing was becoming more accessible to the lower classes. Many British rock climbers were trades people who had lower-middle class occupations. This was especially so in the Northern areas of Britain where tradesmen, manufacturers and shopkeepers dominated the Lake District. Prior to this, one of the greatest booms to the sport came during the second half of the 19<sup>th</sup> Century with the introduction of British railways (Hankinson, 1977). In the 1860's the price of transport dropped, and the working class could suddenly afford to travel. This coincided with the upcoming

prosperity and the introduction of both shorter working hours, and the workers unions. For the first time the young middle class population could afford leisure breaks. This meant climbing in Britain became dominated by a variety of social classes. This social mixture caused an influx of sports men and women, and helped to push the limits of climbing outside of the traditions of the classic alpine style.

The number of people engaging in the sport began to rise rapidly, and so did the level of skill and expectation. However, in comparison with up-and-coming mainstream sports, climbing remained a minority sport with only a few professionals working as guides. It was not until the 1950's that professionalism really began with the introduction of post-war outdoor education in schools. This originated from Kurt Hahn and the principles he taught at both the Gormangast and Salam schools (Miles & Priest, 1999; Priest & Gass, 2005).

#### ***2.1.4 Late 19<sup>th</sup> Century competition***

Cram (1986) categorised the history and progression of rock climbing into four distinct time periods: the easiest way up (up to 1880), the gully and chimney (1880-1900), the ridge and arête (rib) (1890-1905) and the slab and wall (1905- 1986). Since 1905 when climbing and ascending routes on slabs and walls started to grow in popularity, there has been a vast increase in the technical standard of the sport across the world. The transition of climbers moving onto routes with far greater levels of risk and exposure made climbers focus more and more on both their technique and strength. Influencing this progression were many small advances in equipment to aid and protect those who chose to climb hard routes. A climber's social status became less important and more attention was being paid to the individual climber's skill. Now debate raged about ascent styles, whether to record and log climbs, and the use of protection such as a rope when pre-inspecting routes (Thompson, 2011).

Owen Jones, one of the most important historical figures in British rock climbing, initiated the debate with Hasket Smith on the rights and wrongs of using a rope (Hankinson, 1977). Jones was the first to be hoisted up and down a rock face until he knew every move, a technique which is still performed today. Once he had perfected the route he would climb it in front of an audience and claim the 'first ascent'. Many fellow

climbers suggested this wasn't even a form of climbing, yet he made some formidable ascents such as Kern Knotts Crack (graded Very Severe (VS) 4c), and Route Direct on Lords Rake (VS 4a). It was partly under Jones's influence that rock climbing, in Britain at least, became a competitive sport. Jones introduced the first grading system into the sport as a way of making sure people who ascended a route after him, did so in exactly the same manner (Hankinson, 2004). This competitive streak amongst climbers continued, as did the ever growing number of first ascents, until the outbreak of the First World War.

### ***2.1.5 The rise and fall of climbing through the early 20<sup>th</sup> Century***

Of the 68 members of the Fell and Rock Climbing Club who served in the First World War, nineteen were killed and numerous others were severely injured (Thompson, 2011). Throughout the war the women of Great Britain tried to keep the sport alive. The first female ascent happened on the classic line Hope (Very Difficult (VD)) on Idwal Slabs in North Wales (Hankinson, 1977). However, when the war finally ended the thought of rain, mud and vermin were reminders of the death caused by war, and so rock climbing in the UK all but ceased for many years. However, the standard of climbing ability in the Alps continued to grow, particularly amongst the Austrian and German climbers who had started using pitons to protect themselves. British climbers refused to use such forms of protection on mass as they had comparatively minimal *crag*s at home and they believed in preserving the rock for the challenge, and consequently Britain was left behind.

The Wall Street crash in 1929 and the consequence of its effects on world trade saw mass unemployment around the globe. In Britain, people were sacked and wages were cut. For the first time in recent history large groups of young people had significant amounts of leisure time, although they had virtually no money. In depressed industrial towns throughout the North of the country, clubs, which provided low cost activities such as climbing began springing up. Transport became cheaper as the railway prices dropped further. The private motorcar was introduced, and by 1930 there were 2.5 million cars in Britain alone. In 1930 the Youth Hostel Association (YHA) was born and by 1939 it had over 83,000 members. Hostels sprung up amongst Britain's most popular climbing *crag*s and the YHA began to run courses in rock climbing. Rock

climbing began to pick up again and climbers headed to the hills almost every weekend, achieving high levels of both mental and physical strength. Equipment drastically started to improve, rope became available to buy and borrow from clubs, and windproof clothing was invented along with some other specialised climbing equipment. Clubs started arguing for access to mountainous regions and crags for climbing and by 1939 the Mountain Access Bill was passed (Thompson, 2011). Following this, the increase in access and the popularity of the sport boomed, and further public demands were placed on the government. By 1949 the National Parks and Access to Countryside Act was passed.

#### ***2.1.6 Rock climbing through the end of the 20<sup>th</sup> Century***

By the beginning of the Second World War people's opinions and beliefs differed from those seen in the First World War, they had become more resilient and were tougher (Thompson, 2011). Climbers had become more focused, they had the physical and mental strength to climb 90° faces in high exposed places. Far fewer members of the climbing clubs died during the Second World War, and so climbing as a sport had continued. The British Armed Forces practised in the Welsh hills and mountains for the events of the D-day landings. This helped to keep the sport current and alive during a challenging and difficult time. By 1945 the Second World War was over and there was an overwhelming desire to build a new and better future. This was reflected in the landslide victory of the Labour Party in 1945. Working class climbers became more affluent and social cultures changed, people flocked to the crags on mass with new revamped attitudes of strength and romanticism, and a new persona in climbing emerged.

#### ***2.1.7 A new breed of rock climbers***

The 1950's and 60's gave rise to the 'hard man' of British rock climbing which was seen by many as the start of the modern climbing era. New hard bold routes began to be ascended on mass. Names of climbers such as Joe Brown (the 'Baron'), Don Whillans (the 'Villain'), Ron Moseley and Joe 'Morty' Smith became legendary, and at the time almost mythical to some. They travelled from Derby to North Wales, to the Alps and in

the 1950's and 60's they began raising the bar in a huge way. A way that some thought would never be possible. Brown alone completed almost every route in North Wales with ease. He then continued to quickly put up over 600 new routes, a feat which has never been repeated in the UK.

Before the war there were as many women as there were men in the sport. However, post-war they were considered not physically strong enough and males began to dominate the climbing scene, although this wasn't to last long. In the 1950's the first specialised climbing shops opened, and the first published guide, 'Climbing in Britain' was written, selling 120,000 copies (Thompson, 2011). The 1950's and 60's climbing excitement was not just confined to Britain. Walter Bonatti put up extraordinarily tough routes on the Dru in the Alps, in the USA the Nose on El Capitan saw its first ascent taking just over nine months, and in the Himalaya for the first time the 8,000m barrier was broken with the ascent of Annapurna.

#### **2.1.8 *Advances in rock climbing equipment***

It was not just the brave and confident nature of the new generation of rock climbers that helped to increase the severity of climbs being attempted, but the availability and sophistication of the equipment they used. This combination led to vast increases in competitiveness and performance across the globe. Post-war, surplus supplies of karabiners could be bought cheaply, Vibram rubber soles started to replace hob-nailed boots, and in 1980 Boreal released the first sticky rubber shoe called The Fire. Nylon ropes, which were used to tow gliders were shown to be 66% stronger than their hemp counterparts and absorbed the energy of the falls rather than transferring it straight to the climber and belayer (Thompson, 2011). The 1950's saw the rise of passive protection in the rock; a limit of two pitons was the unofficial maximum a climber could use in a single climb (Brown, 1969). Other methods included using pebbles with string wrapped around them and slings with knots in. These could be wedged into cracks to protect a climber from a significant fall. By the end of the 1960's threaded nuts that were specifically designed for climbers were machine drilled and readily available. This sport specific technological boom saw huge increases in climbing performance over the coming years, as climbers became comfortable with taking leader falls. Climbers took

pride in the British traditional style of ascent using little or no permanent protection, and they were considered a bold breed amongst a world of rising climbing stars.

During the 40 years which followed the rejuvenation of rock climbing, the climbing community saw unprecedented improvements and advances in performance throughout the world. Rock climbing grades drastically increased across all disciplines during this period. Table 2.1 presents the significant ascents that have taken place across the world over the past 40 years. These ascents vary from almost seemingly impossible boulder problems to long sport climbs of 9+, and free ascents and free solos of 6c+ (29 Ewbank) on routes in excess of 3000m (often completed in a matter of hours).

**Table 2.1 A list of the most significant ascents in the history of rock climbing from 1970 through to 2012 (grades converted to Ewbank using Draper et al. (2011) Appendix G).**

Date	Climber/s	Grade	Route Name	Location
<b>1970's</b>				
1970	Bernd Arnold	6a (19)	Schwager N-face	Elbe Sandstone Mtns
1971	Al Rouse	E5 6a (19)	Positron	Gogarth, N-Wales
1974	Jim Holloway	V13	Slapshot	Colorado USA
1976	Mick Fowler	E6 6b (20)	Linden	Curber, Derby, UK
1976	John Bachar	E3 6a (19) 1 <sup>st</sup> free solo	New Dimensions	
1977	Ray Jardine	E7 6c (22)	Phoenix	Yosemite, USA
1979	Tony Yaniro	E7 7a (24)	Grand Illusion	Sugarloaf, CA, USA
<b>1980's</b>				
1980	John Redhead	E7 6b (20)	The Bells	Gogarth, N-Wales
1983	Ron Fawcett	E7 6c (22)	Masters Edge	Millstone, Derby, UK
1985	Wolfgang Gullich	E9 7a (24)	Punks in the Gym	Mt Arapiles, Aus
1986	Jonny Dawes	E9 6c (23)	Indian Face	Clogwyn, N-Wales
1986	Antoine Menestrel	7a (24)	La Rage de Vivre	Buoux, France
1987	Wolfgang Gullich	7b (25)	Wallstreet	Frankenjura Switzerland
<b>1990's</b>				
1990	Ben Moon	8c+ sport (34)	Hubble	Raven Tor, UK
1991	Wolfgang Gullich	9a sport (35)	Action Direct	Frankenjura Switzerland
1992	John Middendorf & Xaver Bongard	A4+, WI4 (18)	The Grande Voyage in 18days	Great Trango Tower, Karakoram
1993	Lynn Hill	6b (20)	The Nose (1 <sup>st</sup> free climb)	El Capitan, Yosemite, USA
1995	Fred Rouhling	9a sport (35)	Akira	Charente, France
1996	Alexander Huber	9a+ sport (36)	Open Air	Schleierwasserfall, Austria
<b>2000+</b>				
2000	Neil Bentley	E10 7a (24)	Equilibrium	Burbage, Derby, UK
2001	Chris Sharma	9a+ sport (36)	Realization	Ceuse, France
2006	Chris Sharma	9a+ sport (36)	Es Pontas (Free solo, deep water)	Mallorca, Spain
2006	Dave MacLeod	E11 7a (24)	Rhapsody	Dumbarton, UK
2007	Dani Andrada	9b sport (37)	Ali Hulk Direct	Rodellar Spain
2008	Chris Sharma	9b (37)	Jumbo Love	Clark Mtn, CA, USA
2012	Adam Ondra	9b+ sport (38)	The Change	Flatanger Cave, Norway
2012	Adam Ondra	8a Free Climb (29)	Compressor route	Cerro Torre, Patagonia
2012	Dai Koyamada	V16	The story of two worlds	Cresciano, Switzerland



## **2.2 Competitive international rock climbing**

At the beginning of the 1970's the first structured rock climbing competitions in Great Britain started to appear in the form of speed climbing events. The basic idea was that climbers would race against the clock to try and ascend a section of outdoor crag as fast as possible. The standard of climbers at the competitions improved as did the number of competitors. By the 1980's indoor rock climbing gyms had begun to appear to aid with training. These gyms were very basic using old wooden blocks and chipped bricks for holds (Gregory, 1993). As the numbers of climbers entering the sport continued to increase, rock-climbing gyms started to appear all over the world. In the early 1990's indoor rock climbing was clearly a sport in its own right.

In the 1990's competitive rock climbing in Great Britain was behind the rest of the world. The birthplace of competitive rock climbing was in the Union of Soviet Socialist Republics (USSR) during the 1940's. However, competitions were reserved only for members of the Soviet Union until the mid 1980's. In 1985 climbers' throughout the world were invited to "Sportroccia" in Italy for the world's first difficulty competition on an outdoor crag "Valle Stretta". The event was a huge success with thousands of spectators, and so it was repeated in 1986. Following the achievements of the outdoor event, the French pushed the Union Internationale Des Associations D'Alpinisme (UIAA) to develop an international series of events, and to train both judges and forerunners for assessing speed and difficulty in competitions. In the early 1990's events were created across Europe, Japan and the US and from here it was decided that they should be on artificial indoor walls. In 1991 the first Indoor World Championship was held in Frankfurt, Germany (this still occurs every two years). In 1992 the first World Youth Championships took place in Basel, Switzerland. By 1997 indoor competitions had become so popular that the International Council for Climbing Competitions (ICC) was formed inside the UIAA to guarantee a common standard at competitions throughout the world. In 1998 the sport began to expand once more with the introduction of bouldering to the championships. In 2006 the UIAA decided to support the creation of an independent international federation to govern the sport as it had grown. On January 27<sup>th</sup> 2007, 48 federations from around the world convened to found the International Federation of Sport Climbing (IFSC). Amongst the countries involved, there was unanimous support for the new byelaws and statutes that had been laid down. On December 10<sup>th</sup> 2007 the IOC provisionally welcomed the IFSC into the Olympic movement. Official acceptance by the IOC was granted on February 12<sup>th</sup> 2010

and on the 4<sup>th</sup> July 2011 the IOC Executive Board decided to move sport climbing on to the short list for the 2020 Olympic Games.

## **2.3 Grading systems**

The following subsections aim to provide an overview of the development of grading systems as well as some of the difficulties for scientists wishing to gain a psychological and physiological understanding of the disciplines within sport. A description and comparison of the major grading systems used in rock climbing and bouldering can be found in Appendix A and Appendix G of this thesis.

### **2.3.1 *A generation of competition***

Rock climbing as a sport stemmed from mountaineering, as enthusiasts had become braver and braver, stepping out onto the slabs and rocky ridgelines of mountains in search of different, harder ways to ascend mountains. It was many years after the sport of mountaineering was defined that the first grading system was implemented. As previously mentioned in section 2.1.4, Owen Jones was the first person known to introduce a grading system. He did this so that others would ascend his routes in the same manner as he had done. Since these early days of class, structure and aristocracy within the sports of mountaineering and climbing, numerous grading systems have been developed as the sport has grown. Mountaineering encompasses many forms of climbing during any one single ascent and includes styles such as: walking, scrambling, ice climbing, mixed climbing and rock climbing (Soles, 2008). As mountaineering is considered to be one of the most dangerous sports in the world, due to a plethora of unpredictable external factors (such as rapid weather changes), the systems for grading a mountaineering route are vastly different from any other area of climbing.

### **2.3.2    *The difficulties of grading rock climbing and its disciplines***

During the last century the sport of climbing has grown and developed in such a way that rock climbing is now a generalized term for many different styles and disciplines of ascent, on both artificial and natural walls. Each discipline requires a unique form of mental and physical strength (Horst & Fleming, 2010). Grading a rock-climbing route is difficult, if not sometimes impossible. As every climber perceives a route both physically and mentally differently, the severity and technical difficulty of a route is often objective to the individual and their characteristics. Furthermore, egotistical and excited views of an ascent have been known to elevate a route's difficulty by a grade or two. The most recent example being James Pearson who ascended the 'hardest traditional route in the world' *Walk of Life* given the grade of E12, 7a. After a quick repeat ascent by several professional climbers the route has been given a range of grades, as low as E9 6c (by Dave MacLeod). This problem is not limited to new, hard traditional climbing, but is an age-old problem which affects the grading systems of all disciplines in rock climbing. It was Donald Robertson in 1908 who said 'a truly honest account of a climbing day has yet to be written, and it remains a truth, almost universally acknowledged that there are two approaches to writing about climbing: exaggeration or understatement' (Unsworth, 1994). Clearly this still remains the case today and poses the same problems for both rock climbers and researchers alike.

### **2.3.3    *Traditional climbing***

Traditional climbing is one of the oldest disciplines of rock climbing. The climber ascends a route using a rope and places running removable protection along the way; this protection can be removed by the second who ascends the route after the leader. Traditional climbing is seen as one of the purest styles of ascent (after soloing) as it leaves relatively no trace of the climber being there and the rock remains undamaged for future climbers (Lewis & Cauthorn, 2000). Grading traditional rock routes is difficult as it depends on many things: rock quality, mental state of the climber, technical difficulty and the number of opportunities there are to place protection. The two main concerns for a climber inspecting a grade or route are the level of technical difficulty, and the availability of protection on the route.

The British traditional grading system appears to be the most comprehensive, using an adjective system for protection and a numerical scale for technical difficulty. The system allows a grade to suggest that a climb is technically very hard but it has lots of opportunities to place protection, making it technically hard but relatively safe. Conversely it may be a technically easy climb with little protection, and so the consequence of a fall could be severe. Other grading systems such as the Yosemite Decimal System (USA) and Ewbank (Aus/NZ) scales do not allow for such differentiation in the grade as they use purely a technical difficulty grade. The climber often relies on a guidebook's description to fill in the missing information about the level of protection and severity of a route.

#### **2.3.4    *Sport climbing***

Sport climbing, which relies on pre-placed protection in the form of bolts, was developed much later than traditional rock climbing (Hill, 2007). It was in 1927 that two German climbers, Joe and Paul Stettner arrived in Colorado. The climbers had ordered *pitons* from Munich and decided to climb the East face of Long Peak (14 Ewbank). Their ascent became infamous within the USA. In the same year Laurent Grivel designed the first mechanical tools for climbing, the expansion bolt and the drill. These tools were designed to allow rock climbers to be able to ascend any route with aid. In more recent years sport climbing has become commonplace amongst some crags, and yet it is seen as a complete violation of rock in others. One of the considerations for bolting a route, as opposed to using traditional gear, is the quality and strength of the rock. However, if the face is climbable but has no place for natural protection then it is often considered fair to bolt. This generalised rule is not the same in all countries; much of the USA and Europe will bolt a route even if it has sufficient protection, whereas in the UK it is considered almost vandalism. Furthermore, in many parts of the world such as Japan, China, Australia and New Zealand, some rocks are considered to be sacred, and therefore defacing them with bolts is banned. Grading sport routes is generally suggested to be easier than traditional routes as the style of climbing involves less mental strength, as they are often less dangerous. The consequences of a fall onto a pre-placed, drilled expansion or glue bolt are far less than taking the same fall on a small wire or nut (traditional gear). However, the same problems arise with the objective nature of providing the climb with a technical grade.

### **2.3.5 *Bouldering***

Bouldering, which often involves difficult and powerful moves close to the ground (Macdonald & Callender, 2011), is almost impossible to date with a first ascent. However, it is thought to have started in France in the late 19<sup>th</sup> Century as climbers practiced technical moves for longer routes in the Alps (Montchaussé, Montchaussé, & Godoffe, 2001). The Bleausards are said to have arrived in Apremont, France in 1897. They made the first documented records of scrambling on boulders here (Montchaussé et al., 2001). After this, the date depends on the definition of bouldering used; some believe it wasn't until Chris Sharma in the early 1990's, and some suggest it was much earlier with John Gill bouldering in 1950's (both in the USA) (Montchaussé et al., 2001). Grading boulder problems is almost as fraught with issues as grading traditional climbing is.

A grade comparison between the major grading systems in bouldering is shown in Appendix B however, not all grading scales use the same criteria. Shermans V-scale was designed in the 1990's for use in Huecco Tanks (USA) and is solely used to describe the technical difficulty of a climb. The British technical scale was often used in the UK until about 2000 when the V-scale took over as the predominant grading system. Unfortunately, neither of these grading systems matches the Fontainebleau scale, which not only takes into consideration the technical difficulty, but also the exposure, height and consequence of a fall. As Fontainebleau is one of the major bouldering venues in the world, these discrepancies between grading systems make comparisons difficult. This, blended with the objective nature of technical difficulty makes comparing grading between countries problematic.

### **2.3.6 *Grading issues for sport scientists***

As previously mentioned, the differences in grading systems and the objective nature of grading makes it difficult for people who climb for recreation, and for those who choose to become professional and compete at international levels to determine the difficulty of a route. However, it is not just rock climbers that have struggled with the lack of homogeneity in the grading systems. Scientists investigating a wealth of physiological, psychological, anthropometric and biomechanical parameters have also found confusion and confliction. The most commonly used grading systems around the world (USA,

British Technical and French Sport) prove to be fraught with difficulty if any statistical analysis is required (Draper, Brent, Hodgson, & Blackwell, 2009; Watts et al., 1993a). Watts et al. (1993a) was the first author to attempt to resolve this problem with the introduction of a number conversion. This was then followed by Schweizer and Furrer (2007), Padrenosso et al. (2008), Llewellyn, Sanchez, Asghar, and Jones (2008), Michailov, Mladenov, and Schöffl (2009) and Draper et al. (2009) who all made similar conversions which could be easily used with statistical packages.

## **2.4 Summary**

Records of mountaineering date back to before the 18<sup>th</sup> Century. The first rock climbs were completed by mountaineers who wished to ascend new harder routes in the hills. The first recorded rock climbing ascent of Naples Needle in the Lake District (UK) saw the beginning of what is now one of the most intense and captivating sports. Throughout the mid 19<sup>th</sup> and 20<sup>th</sup> Centuries, rock climbing grew in popularity, and the level of performance dramatically increased. Recent years have seen the sport become increasingly competitive. Furthermore, rock climbing has branched into numerous disciplines, each one arguably a sport within its own right. As scientists have attempted to define the physiological and anthropometric profiles of these groups, they have stumbled across numerous barriers, including issues surrounding route grading, matching route profiles and the general dynamic nature of the sport. The following section 'Review of Rock Climbing Research' describes in detail the progression of the existing research in rock climbing, from the early editorial works of Barford (1945) to the most recent physiological studies attempting to define the energy system contributions and hormonal responses.

## **Review of Rock Climbing Research**

### **3.1 Growth of rock climbing**

The influx of climbers into the sport of rock climbing escalated throughout the UK during the mid 1990's; the British Mountaineering Council (BMC) suggested that participation rose from 25,000 to over 74,000, resulting in over 300 individual clubs being formed (BMC, 2009). The same trend was seen in America; the American Alpine club saw its membership exponentially increase between 1993 and 2007 from 2,000 to 8,000 members (Powers, 2011). Due to this exponential growth, coupled with the large increases in technical performances over the past three decades, and the acceptance onto the 2020 Olympic Games short list, gaining an understanding of the physiological demands of the sport has become increasingly important.

Although pioneers have been rock climbing as a 'sport' per se for the best part of the last one and a half centuries, it is really only since the 1980's that a significant body of empirical based research about the sport began to emerge. As previously mentioned (section 2.1.3), the changes in social structure and class, combined with increased leisure time and a greater disposable income meant that more and more people took up rock climbing as a recreational activity. This increased in participation coincided with, and in part caused, the emergence of research into the sport during the mid 20<sup>th</sup> Century. Since then the intensity and specificity of research has grown significantly across all disciplines, albeit the growth is limited compared to other sports, including those with limited participation. When 'rock climbing' is entered into the search engine PubMed, 83 articles that have 'rock climbing' in the title are displayed. Furthermore, when the same search is entered into Google Scholar, there are 398 articles. The distribution of these journal articles is presented in Table 3.1

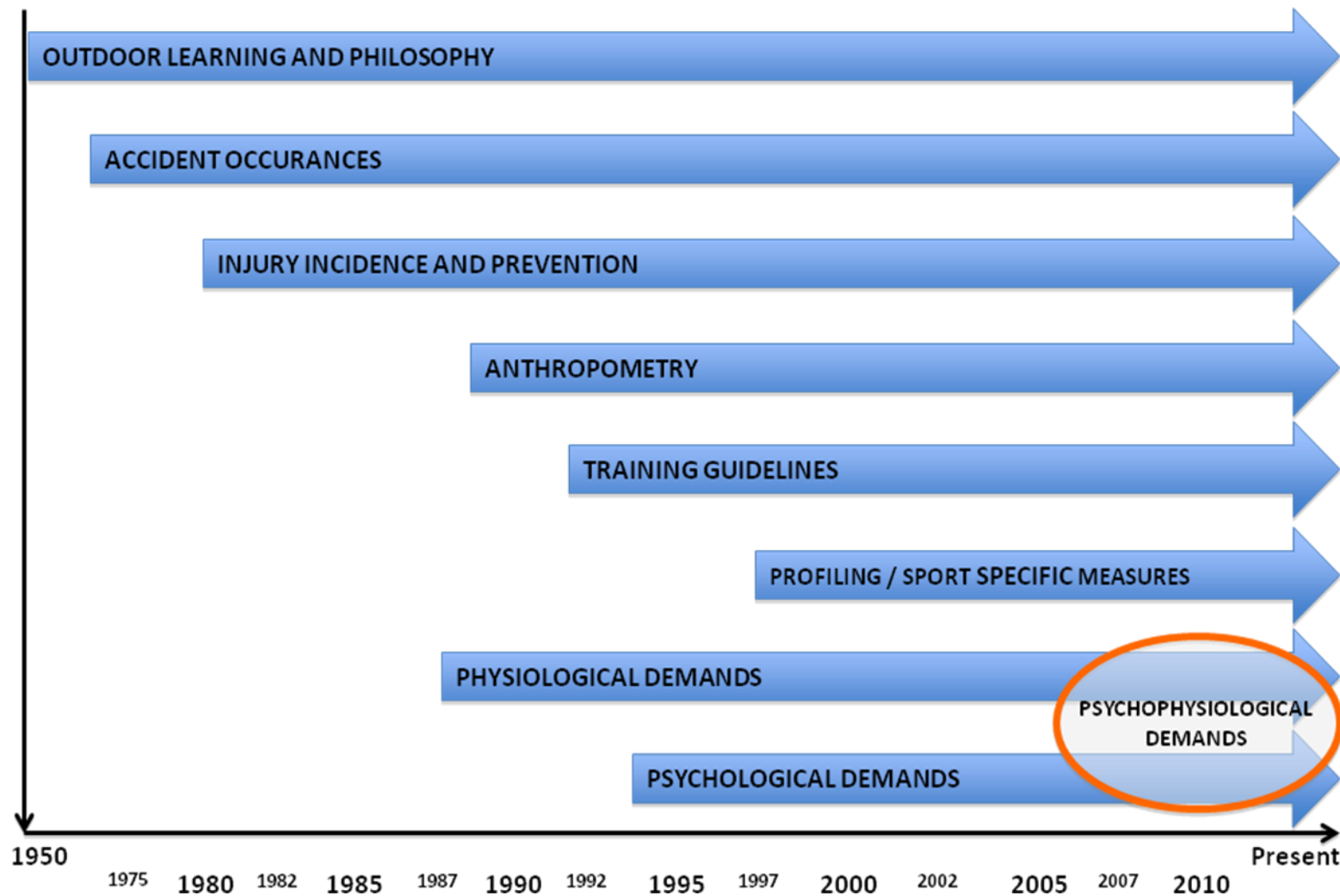
**Table 3.1 The distribution of journal articles with 'rock climbing' in the title (search engines; PubMed and Google Scholar) from pre-1990 to 2012).**

Research dates	Number of <i>PubMed</i> title articles	Number of <i>Google Scholar</i> title articles
Pre – 1990	10	30
1991 – 2000	20	94
2001 – 2010	36	225
2011 – 2012	17	49
<i>Total</i>	83	398

Compared with more mainstream sports such as golf, running, tennis, and cycling, knowledge of sports science orientated performance based rock climbing is still very young. The scientific components which make up a golf swing or a perfect tennis forearm swing have been extensively researched for a significant period of time. But the technical aspects of rock climbing have only been investigated for the past 30-40 years. As the IOC have now recognised rock climbing as a sport, and placed it on the short list for the 2020 games, it is expected that the increasing research base, particularly that focusing on performance enhancement, will continue to grow.

Figure 3.1 highlights that, since the 1950's, published research into the sport of rock climbing has progressed through the following stages: Epistemology of moral growth through climbing (late 1950's onwards), mountaineering based accidents (1960's onwards), incidence of injury (late 1970's onwards), anthropometry, training guidelines and profiling (mid-late 1990's onwards), physiological aspects (late 1990's onwards), psychological aspects (late 1990's onwards) and more recently psychophysiological components (2000's onwards). This timeline of empirical based research will make up the structure of the following review of literature.





**Figure 3.1 Schematic representation of the development, and systematic research focus for rock climbing.**

### **3.2 Early rock climbing studies**

The first known journal article which had a sport science focus was an editorial piece by Barford (1945). Barford was the secretary of the BMC at the time, and he wrote an editorial piece in the British Medical Journal. The article asked for readers to present him with cases of falling injuries, as the BMC were anxious to secure evidence of the effects of falling on both the leader and second. However, the majority of research that immediately followed this was based around outdoor learning or using rock climbing as a medium. It has long been suggested that outdoor education and outdoor sports such as rock climbing can increase a person's moral fibre, interpersonal skills, self-concept and awareness of locus of control (Hattie, Marsh, Neill, & Richards, 1997; Priest & Gass, 2005; Wattchow & Brown, 2011). The British philosopher John Stuart Mill recognised the importance of outdoor spaces for personal development during the mid 19<sup>th</sup> Century, a time when many parts of the Westernized World were experiencing mass urbanisation (Thompson, 2011). Kurt Hahn was the founder of Outward Bound and the person who formalised the use of adventure as an educational process. Hahn suggested that certain outdoor activities in open spaces such as rock climbing, helped to bring out the best leadership qualities in people by steering them away from the influences of a stressful urbanised life (Miles & Priest, 1999). Perhaps for these reasons, one of the earliest known rock climbing studies examined the use of rock climbing as a therapeutic rehabilitation tool (Bienia, 1962). Bienia (1962) observed 20 patients during a rehabilitation program. The author reported 'complete security' in the experience and suggested that it had favourable effects on the patients' self-confidence, as well as their muscular strength, range of motion and precision of movements.

### **3.3 Accident and injury incidences**

The latter part of the 20<sup>th</sup> Century appears to be a dividing point in climbing research. Authors continued to investigate and expand upon the use of climbing and other adventurous activities as tools for moral growth, and the understanding of group dynamics. However, a new wave of quantitative research into accident and injury rates began to emerge. As the sport grew in popularity, so did the rates of accidents and injuries. The first attempts to quantify these incidences in climbers, focused on a mixture of rock climbing and mountaineering (McLennan & Ungersma, 1983; Reid, Doyle, Richmond, & Galbraith, 1986; Ridden, 1983). Ferris (1963) suggested that per

year there were 18,722 days worth of mountain climbing from the entirety of the USA mountaineering population. By 1987 this number had grown to between 25,000 and 50,000, and as a consequence, accident rates were increasing significantly (Bowie et al., 1988). Although the sport was rapidly growing, Bowie et al. (1988) suggested that until 1988 there had not been a report which documented the rates of injuries in lowland climbing areas within the USA. Across the globe in the European Alps, Foray et al. (1982) suggested that within the Chamonix-Mont Blanc region, out of the 1819 known mountain climbing accidents up to 1980, 69% were classified as a 'trauma', 22% as 'exposure to the cold' and the rest consisted of 'mountain sickness', 'fatigue' and 'accidents due to lightening strike'. Following these early descriptive studies, individual regions within countries continued to quantify the number of mountain climbing based accidents that presented themselves in both hospitals and general practices across the developed world (Bowie et al., 1988; Schussman & Lutz, 1982; Wyatt, McNaughton, & Grant, 1996).

The first substantial set of published research articles which were specific to rock climbing attempted to highlight the increasing incidence of injuries which had started to occur around the late 1980's – early 1990's (Bannister & Foster, 1986; Bollen, 1988; Cole, 1990; Wyatt et al., 1996). This was probably due, not only to the large number of people recreationally entering the sport (Bollen, 1988), but also because competitive speed climbing had begun to spread from the USSR to the rest of the world. Bannister and Foster (1986) first highlighted the need for general practitioners to have a greater awareness and understanding of rock climbing associated injuries. The authors suggested that in their local area (Leeds, UK), several cases of training related injuries had been presented to general practitioners. However, accurate diagnoses were often substantially delayed due to a lack of sport specific knowledge.

As improvements were made in safety equipment, accidents occurred in the traditional style of rock climbing causing injuries such as breaks and head traumas diminished in the mid 1980's. However, as the number of rock climbers participating in competitive climbing grew, so did the number of training induced injuries (Bannister & Foster, 1986). These increases in accidents and injury incidence were not just in the UK, but also in the USA. Although all of these were not fatal, many acute traumas (from breaks to tendinitis) resulting from training injuries and falls, became apparent (Bannister & Foster, 1986; Cole, 1990).

Modern day rock climbing, defined here as post-1970, has evolved from what was once a recreational activity conducted on easy slab and vertical walls, into a sport that encompasses difficult overhanging and often crimpy routes. Consequently, this puts an enormous strain on the upper body, particularly finger and toe extremities. Routes have become so steep and overhanging and the holds are now so small that they often require only one finger, or they are so sloped that the palm can barely grip them. This extreme wall/cliff angle blended with the often virtually non-existent holds, places the climbers at a far greater risk of sustaining an injury to one or more of the upper body extremities (Bollen, 1988; Jebson & Steyers, 1997; Paige, Fiore, & Houston, 1998; Rohrbough, Mudge, & Schilling, 2000; Rooks, Johnston, Ensor, McLntosh, & James, 1995). Recent published works began to report injuries such as shoulder joint capsule damage, tendonitis of the wrist and fingers, finger tenosynovitis, interphalangeal and metacarpophalangeal joint problems (Jones, Asghar, & Llewellyn, 2008; Schöffl & Schöffl, 2007). Furthermore, even large synovial joint problems such as elbow and shoulder complaints were being reported (Förster, Penka, Bösl, & Schöffl, 2008; Wong & Ng, 2009). These injuries had either previously not been experienced by climbers, or they had not been reported upon as most published research was conducted by the accident and emergency (A&E) departments. Climbers with these types of injuries would not have been admitted to A&E, as the injuries were not serious enough, and therefore would have been unreported in studies (Bowie et al., 1988).



Slab climbing pre-1970

Over-hung climbing post-1970

**Figure 3.2 The differences in styles of ascent seen pre and post-1970.**

During the late 1970's and early 1980's there was a marked increase in the rate of overuse and training based injuries (Bannister & Foster, 1986; Bollen, 1988; Rooks et al., 1995). As previously mentioned, these may have been caused by the improvements in safety equipment which allowed for a more technical level of climbing, and a higher grade of competition (Bollen, 1988). However, the introduction of indoor climbing walls has also been suggested to be a significant factor closely associated with the emergence of overuse injuries in the late 1980's (Rooks et al., 1995). Indoor climbing walls were developed during the mid 1960's in the UK because mountaineers wished to train throughout the winter months (Wittelstaedt, 1997). It was suggested that any top climber wishing to remain competitive would now be required to train on a daily basis throughout the year (Bollen, 1988). Climbers originally attached bolted wooden holds into a cement surface resulting in an artificial wall (Wittelstaedt, 1997). This was quickly adapted by the French who changed the holds to resin blocks that were sanded down to feel like real rock (Gregory, 1993). This new way of increasing training time quickly became popular amongst rock climbers, and the number of climbing walls throughout the world grew rapidly. In Belgium in 1985 there were only two known indoor walls, and by 1990 this number had increased to over 50 (Wittelstaedt, 1997). In 1990 Illinois State University (USA) conducted a survey, which determined that 25 universities and businesses had indoor climbing walls across the USA (Morford, 1991). This increase in the number of indoor climbing walls was seen across the world, and had a major influence on both the popularity of the sport and on climber's ability levels. As a result an even greater number of overuse and training based injuries occurred (Bannister & Foster, 1986; Bollen, 1988; Rooks et al., 1995). Consequently, this has led to a continued research interest in both injury quantification and prevention within the sport.

The fore mentioned increases in injury seen in rock climbing became a concern for the BMC. In the late 1980's the BMC established a committee to investigate safe and appropriate training methods for rock climbing. Steve Bollen, an orthopaedic surgeon and medical advisor to the BMC was asked to investigate the injuries sustained during intensive periods of rock climbing and training. By identifying the problem areas, it would be possible to develop and present appropriate and safe training schedules. The author distributed 100 questionnaires to a variety of rock climbers and received a return rate of 86. It was reported that amongst the 86 participants returning questionnaires, there were 115 injuries that were symptomatic for 10 days or more, and 89% of these

were to the upper extremity. One of the most interesting findings of the study was that almost half of the reported injuries occurred during training. The level of climbing difficulty at which the injuries occurred was suggested to be ‘fairly evenly’ distributed amongst the extreme grades (see Appendix A 12-1 for a grades comparison table (Giles, Rhodes, & Taunton, 2006)). Interestingly, only 21 individuals had sought medical attention, and 78% of those sought attention from their general practitioner. It was noted that the patients had been unimpressed with the treatment provided.

After the first injury study by Bollen (1988) there was an exponential increase in the amount of injury-based research being conducted. Table 3.2 aims to summarise the main focal points of injury research carried out from 1980 to 2012, this includes: possible injuries sustained during rock climbing, potential training adaptations, injury prevention and possible surgical procedures to fix and repair injuries sustained during rock climbing.

**Table 3.2 Selected journal articles revealing the progression of injury based research in rock climbing from 1986 to 2012.**

Date	Authors	Study Aim/s	Key Finding/s
1986	Bannister & Foster	To present 4 injury cases of climbers (n=4).	Current diagnosis techniques are not adequate due to lack of sport specific awareness
1988	Bollen	Identify common injuries specific to rock climbing (n=86).	Upper body extremity injuries occur in climbers who train all year round. A lack of awareness about training methods.
1988	Bowie & Allen	To quantify the accident and injury incidence in Yosemite National Park (n=220).	50% of injuries were to the skin or subcutaneous tissue. 28% were lower limb fractures.
1995	Rooks et al	Quantify injury patterns in recreational climbers (n=39).	89% of climbers had at least one major injury; over 50% of these involved the hand and wrist. These included tendonitis (50%), pulley injury (19%) and carpal tunnel syndrome (11%).
1997	Jebson & Steyers	To inform medical practitioners of the right treatment for climbing based hand injuries.	Due to the controversy surrounding surgical procedures, climbers who sustain ligament tears, locked digits, flexor tendon avulsions or ruptures should be referred.
1998	Paige et al	To compare injuries in traditional and sport climbing (n=398).	Traditional climbing elicited falling injuries. Sport climbing elicited injuries on stressed finger joints. Concludes that climbers need to be educated on the limitations of the fingers.
2000	Rohrbough et al	Overuse injury to the flexor tendon sheath in elite climbers (n=42 national USA climbing championships)	Elite climbers frequently experience closed traumatic pulley ruptures.
2001	Peters	Provide an overview of orthopedic problems in sport climbers.	Recognition that climbers need educating on overuse syndromes and furthermore appropriate diagnosis is required by physicians.
2001	Wright et al	To determine the frequency of overuse injury in indoor rock climbing (n=295).	The most dedicated climbers are at the most risk of injury. Authors suggest there can be no recommendations to reduce injury.
2001	Bryant et al	To highlight awareness of open lateral ligament injuries of the ankle in rock climbers (n=2).	Suggest that no attempt to deal with lacerations should be made until examination of the lateral collateral ligaments has been completed under anaesthetic.
2004	Voulliaume et al	Contributions to pulley rupture and factors associated with postoperative rehabilitation are studied (n=12).	Post-injury surgery is the only treatment to allow climbers to return to the sport and potentially improve performance.
2006	Schöffl et al	To evaluate injury risk associated with rock climbing competition (n=443).	Indoor climbing competition has a low injury and a very good safety profile.
2007	Schöffl et al	To determine whether radiographic adaptations seen in young climbers leads to the early onset of osteoarthritis over a 5 year period (n=10).	Intensive training leads to adaptive changes such as cortical hypertrophy and broadened joint bases in the fingers. Osteoarthritic changes are rare but a longer study is required.
2007	Schöffl & Schöffl	Injury and overuse review	While finger flexor and pulley injuries are well known to be frequent problems, numerous other syndromes are not so well known such as lubrical shift and flexor tendon ganglions.
2007	Roseborough & Lebec	To examine the glenohumeral to scapulothoracic ratio in climbers (c) and nc (n=21c, 40nc).	Climbers had a significantly greater ratio than non-climbers, which could be due to the period of time spent in extreme positions in rock climbing.
2007	Morrison & Schöffl	To provide a review based in part, on injury data of physiological adaptations in young rock climbers.	Climbers under 16 should not participate in bouldering competitions or use intensive finger training. The majority of foot injuries resulted from tight or un-natural shoes. Somatotyping for key attributes in elite climbers is incomplete. High intensity training can result in delayed and altered pubertal and skeletal development.
2007	Hohlrieder et al	To reveal whether injury patterns after a fall in rock climbing are determined by harness type (n=113).	Harness type does not influence pattern or severity of the injury experienced.
2009	Förster et al	To investigate the form and mobility of the thoracolumbar spine in rock climbers (n=80).	An increased thoracic kyphosis, lumbar lordosis and a shortened pectoralis muscle characterized "Climbers back". Climbing ability was strongly correlated to postural adaptations.
2009	Wong & Ng	To compare internal and external rotator strength and ratio in sport climbers and non-climbers (n=31c, 27nc).	All work ratios were smaller in climbers vs non-climbers. Clinical implications of the strength differences are yet to be examined.
2011	Schöffl et al	UIAA medical commission injury and classification for mountaineering and climbing sports.	Definitions of injury location, classification, and fatality risk were proposed. The UIAA medical commission recommended the criteria for robust comparisons in future injury based climbing research.

UIAA: Union International des Associations d'Alpinism. n/c: non-climbers

As can be seen from Table 3.2 there has been a shift in the focus of injury-based research in rock climbers over time. During the late 1980's research focused on quantifying injury identification, and recognizing the lack of sport specific treatments in hospitals. By the mid 1990's research had started to quantify injury patterns in rock climbing across the world, and journals were offering medical staff appropriate diagnosis and treatment options for patients. It was during the mid 1990's that training for performance in rock climbing really took off (Horst, 2008). As previously mentioned, injury rates mirrored this increase in training.

During the early millennium recognition of a much wider range of finger and hand based injuries, with more specific and appropriate surgical treatments were being proposed (Peters, 2001; Rohrbough et al., 2000; Wright, Royle, & Marshall, 2001). This was soon followed by new surgical guidelines for both the diagnosis and treatments of a range of hand and finger injuries (Schöffl, Hochholzer, Winkelmann, & Strecker, 2003).

The popularity of competition climbing continued to increase and younger participants began performing at higher levels which equalled their adult counterparts (Morrison & Schöffl, 2007). Consequently, between 2005 and 2012, the research focus highlighted the possible dangers of children under sixteen partaking in bouldering competitions, and conducting intensive finger training (Morrison & Schöffl, 2007; Schöffl, Hochholzer, Imhoff, & Schöffl, 2007). Furthermore, longitudinal studies have investigated possible physiological changes over time, including pubertal and skeletal developments in these young climbers. More recently there appears to be a growing interest in injuries outside of the fingers and hands; both the shoulder and back are currently beginning to receive attention in the literature (Förster et al., 2008; Wong & Ng, 2009).

It is clear from the literature that this increased injury rate was caused by several factors: over training, the growth of indoor walls and the rapid increase in performance. Consequently, the quantity of literature has increased in an attempt to address these issues (Bannister & Foster, 1986; Cole, 1990; Förster et al., 2008; Hochholzer & Schöffl, 2005; Jones et al., 2008; Schöffl, Einwag, & Schöffl, 2006; Schöffl, Hochholzer, & Imhoff, 2004; Schöffl, Hochholzer, Winkelmann, & Strecker, 2004).



### **3.4 Training guidelines**

During the early years of hard climbing, just before the international birth of competitive rock climbing, almost no training guidance existed for the sport. Although this was also often the case for other sports such as football, cycling and running, rock climbing places extreme pressure on the body's extremities and consequently there is a high chance of injury (Jebson & Steyers, 1997; Schöffl et al., 2003; Schöffl & Schöffl, 2007). Therefore, the need for accurate training information is not just important for improving performance but also for injury prevention.

Some of the first known published literature that aimed to provide training guidelines came from books such as *Modern Rock Climbing, free climbing and training* (Skinner & McMullen 1958, revised in 1993) and *Rock Sport, tools, training and techniques for climbers* (Gregory, 1989). These books were written by accomplished climbers of the time who were ascending what was then considered to be difficult routes. Most of the technical information contained within the books that related to climbing aspects such as, set up procedures and rescue techniques, are still considered correct for the time that the literature was published. However, it is not clear from any of the early books (pre-1993) where the authors acquired their physiological, nutritional and training knowledge from. No peer reviewed research can be found within the texts, and so it can only be assumed that most of the information stemmed from the authors experiences as a climber. The intentions of the books are clearly well meant, aiming to improve both skill and performance for the readers. However, in some books such as those written by Skinner and McMullen (1993), the authors could almost be accused of having a hint of arrogance to their writing style. The authors often suggest that they alone are correct and others, no matter how experienced or skilled, need to heed the advice given. The information in these books has led to some potentially misleading facts regarding physical and mental training, as well as dietary requirements.

Gregory (1989) only dedicated eleven pages (of which most are illustrations) of his book to training. The author mainly discussed how to train for cardiovascular (CV) endurance by doing a 20 minute workout at the 'training threshold'. It is suggested that any form of CV exercise would suffice, for example, swimming, rowing, running or cycling. Furthermore, the author suggests that the best way to improve a climbing grade is to lose weight, "the lighter the body the greater the degree of improvement" (p.166) (Gregory, 1989). Readers were suggested to stay away from fats, as these not only make

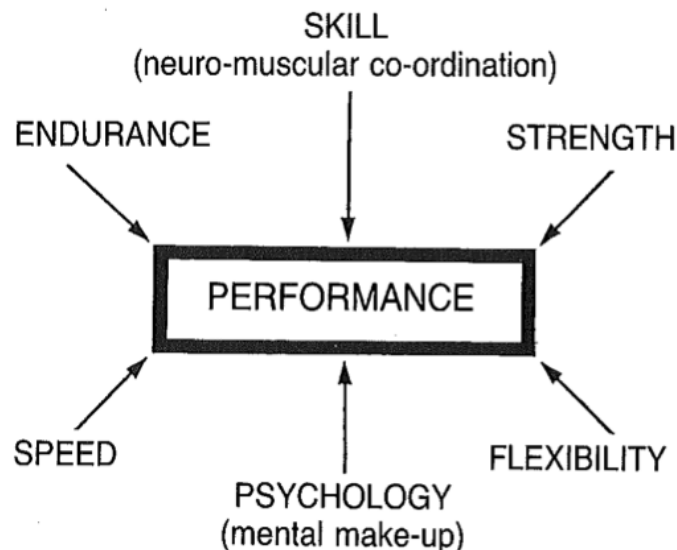
the stomach feel full, but they also have more calories per gram than carbohydrates. Skinner and McMullen (1993) also put a significant emphasis on the need for dieting and losing weight to increase performance. However, in the chapter, 'Diet for the Weight-Conscious Climber' it is recognized that although strength-to-weight ratio is important, body fat weighs less than muscle. It is again suggested that the largest gains in performance will be achieved by reducing body fat. Furthermore, the book does not promote a healthy diet. "Unfortunately, maintaining a good diet will not take off the fat" (p.88) (Skinner & McMullen, 1993). It is suggested that climbers should try and keep their weight down by consuming minimal dairy products, use zero fat milk or tofu drinks for breakfast foods (p.87) (Skinner & McMullen, 1993). These broad statements within the book appear to suggest that all climbers need to follow such guidelines in order to improve their performance, and consequently misguided and inaccurate information is presented.

The books do not just limit themselves to dietary changes to improve performance; the authors also briefly discuss physical training methods. The use of free weights and machine weights in a gym-based environment is suggested to be good for improving climbing specific strength, 'especially in women who often lack power' (Skinner & McMullen, 1993). Gregory (1989) also placed a significant focus on gym based training, and suggests ways in which the exercises can be adapted to become more specific to climbing. More importantly, there is a chapter on injury prevention for rock climbers. The authors suggest the best way to prevent joint injury is to train both sides of a joint, train the agonistic muscles and cycle workouts to fit a routine. This must all be done whilst ensuring the climber does not over train. Although the injury prevention chapter was a good progression from previous books, the information provided on training and injuries is very basic and leaves a lasting impression on the reader. They *must* train in a weights gym as well as on a climbing wall and furthermore, they *must* lose weight in order to improve their climbing grade.

Since the late 1980's and early 1990's, training based literature has notably improved. There were three early books which became excellent guides for avid rock climbers wanting to stay injury free whilst improving their performance: Performance Rock Climbing by Dale Goddard and Udo Neumann in 1993, Training for Climbing by Steve Bollen in 1994 and The Handbook of Climbing by Allen Fyffe & Iain Peter in 1997. The last two were commissioned by the BMC. Performance Rock Climbing was written

by an academic and a prolific climber of the time. The book covers the areas of strength, endurance, tactics and technique in great detail and offers the reader new insights into the potential increases in performance. However, the authors go to great lengths to explain the physiological concepts behind the training advice given, and consequently the lay person descriptions and ideas are applicable and easy to understand. One major flaw of the book is again, the lack of detailed information regarding injury and injury prevention, this section is very basic and has only a scattering of references supporting the text.

The Handbook of Climbing by Fyffe and Peter (1997) appears to be the first book to have included recognised pieces of research in the field, writing sections on training for both the physiological aspects (Morgan) and the psychological aspects (Hardy). The book is well structured, well presented and considerably more accurate than the previous speculative training books. Furthermore, it is aimed at a broad range of climbers and does not expound a limited training regime, or focus excessively on foods that *cannot* or *must* be consumed. Figure 3.3 presents the books model, showing the multidimensional aspects of training for climbing including strength, endurance, speed, flexibility and the psychology of the climber.



**Figure 3.3 Training aspects which increase performance ((Fyffe & Peter 1997) pg 332).**

All of the aspects presented in Figure 3.3 are thoroughly covered in the text with many options for sport specific based workouts, and how they fit into macro and meso training cycles. In addition to The Handbook of Climbing, Training for Peak Performance by Soles (2008) and Training for Climbing the Definitive Guide to

Improving your Performance by Eric Hörst (2003 and revised in 2008) were also published around the same time period. These two books became invaluable resources for climbers, and helped to educate and inform them about both the physiological and psychological training needs for a variety of levels of performance, as well as different disciplines within the sport. Both books are exceptionally well written and turn complex scientific training concepts that stem from academic research into a lay person readable comprehensive text, and resource for active climbers and coaches. Climbing: Training for Peak Performance (Soles, 2008) focuses on aerobic fitness as well as strength and conditioning for mountaineering and rock climbing. The book is aimed at a wide range of abilities and disciplines. The main concept of the book is to steer the reader away from the traditional training method of ‘just climb more’ and provide practical, well researched training methods which target the weakest areas of an individual’s climbing fitness.

The improvements in training based texts for climbers over the past few years were not unexpected. As competition climbing began to grow in the early 1990’s and athletes began to push themselves both mentally and physically, there was a distinct lack of research within the sport which aimed to improve training and performance in a safe manner. There was little documentation to really suggest what traits make a good climber, let alone how to train these areas. Before the year 2000, there were only two training based peer-reviewed journal article (Kascenska, Dewitt, & Roberts, 1992; Shirer, 1990). Furthermore, these articles were really aimed at facilitators and university physical education students, who were exploring how to teach rock climbing in schools after the boom of indoor rock climbing walls in the 1980’s (Wittelstaedt, 1997).

One possible reason for such a lack of training based research could be due to the fact that no descriptive data had been published on the anthropometric and strength aspects, which may have defined a top level climber. However, as these areas have begun to be addressed over the past two decades (Grant et al., 2001; Grant, Hynes, Whittaker, & Aitchison, 1996; Mermier, Janot, Parker, & Swan, 2000; Watts, Joubert, Lish, Mast, & Wilkins, 2003), training based research has started to emerge. However, this has been slow and it still often lacks sport specificity. Between the year 2000 and the present, there were only four known peer reviewed journal articles that presented information on improving climbing performance through physiological training: The use of dynamic eccentric-concentric strength training (Schweizer, Schneider, & Goehner, 2007), the use

of sport specific strength and conditioning programs (Phillips, Sassaman, & Smoliga, 2012), evaluating the strength, endurance and flexibility changes in novice climbers over a seven week period (Lopera, Porcari, Steffen, Doberstein, & Foster, 2007) and the effects of two maximum grip strength training methods using the same effort and duration, and different edge depth on grip endurance in elite climbers (López-Rivera & González-Badillo, 2012). As a better understanding of the characteristics of a range of different ability rock climbers becomes more understood, it is thought that with time a greater body of training based research will emerge.

### **3.5 Profiling rock climbers**

There has been remarkable performance based developments in rock climbing over the last few decades. The sport has seen the grade boundaries being continually pushed, and new genres of rock climbing have emerged. As athletes strive to continually push their physical and mental capabilities, researchers have attempted to create and better understand the profiles of rock climbers. Research has tried to depict and describe the anthropometric characteristics (Grant et al., 2001; Grant et al., 1996; Watts, Danbush, Deur, & Gibbons, 1993b), grip and forearm flexor strength (Cutts & Bollen, 1993; Quaine, Vigouroux, & Martin, 2003; Schöffl, Harrer, & Küpper, 2006; Schöffl et al., 2007), develop performance assessment tools (Baláš, Pecha, Martin, & Cochrane, 2012; Bertuzzi et al., 2012; Brent, Draper, Hodgson, & Blackwell, 2009; Draper et al., 2009) and find predictors and indicators of climbing performance (España-Romero et al., 2009; Wall, Starek, Fleck, & Byrnes, 2004).

#### **3.5.1 Anthropometry**

Before reliable and valid training methods could be studied, recognition of what makes an elite climber so exceptional compared to their lesser counterparts needed to be investigated. The quantification and understanding of the anthropometric characteristics involved in rock climbing appears to have been the backbone of performance related research within the sport since the early 1990's. The first major articles attempted to describe the anthropometric, strength, endurance, flexibility and physiological

characteristics of rock climbers (Grant et al., 2001; Grant et al., 1996; Mermier et al., 2000; Watts et al., 1993b).

Watts et al. (1993b) produced the earliest known anthropometric study which sought to investigate the make-up of male ( $n = 21$ ) and female ( $n = 18$ ) rock climbers during a World Cup competition. A wide range of anthropometric data was presented including body mass, height-to-weight ratio, sum of seven skin fold, percentage body fat percentage, free fatty mass, hand and arm plethymography, grip strength and strength-to-weight ratio. It was concluded that both male and female elite rock climbers were moderate to small in stature, had moderate grip strength and had similarly low body fat percentages. Furthermore, it was suggested that the strength-to-weight ratio and body fat percentages were predictors of climbing performance (assessed by the World Cup competition grade). Following this initial study into elite level climbers, several other authors sought to define potential anthropometric differences in a range of ability groups (Grant et al., 2001; Grant et al., 1996; Mermier et al., 2000). Table 3.3 represents all the known rock climbing studies which aimed to either describe or compare the anthropometric characteristics of different ability rock climbers to date.

**Table 3.3 The aims and key findings of all known published rock climbing studies which describe, compare and contrast the anthropometric characteristics of a range of different ability rock climbers.**

Date	Authors	Study Aim(s)	Key Finding(s)
1993	Watts	Describe the anthropometric profiles of World Cup male and female climbers.	Both male and female elite climbers are small in stature, have low body mass and fat %.
1996	Grant et al	Compare the anthropometric characteristics of male non-climbers (n=10), recreational climbers (n=10) and elite climbers (n=10).	Elite climbers have greater shoulder girdle endurance, finger strength and hip flexibility.
2000	Mermier et al	To identify the physiological and anthropometric determinants of sport climbing performance (n=24m, 20f).	The variance in climbing performance can be explained by a component consisting of trainable variables. Findings do not support the belief that a climber must possess certain anthropometric characteristics.
2001	Grant et al	To compare the characteristics of female non-climbers (n=10), recreational climbers (n=10) and elite climbers (n=10).	Elite female climbers have a greater finger strength than both recreational and non-climbers.
2003	Grant et al	To compare climbing-specific finger endurance in intermediate rock climbers, rowers and aerobically trained individuals (n=27).	Climbers have a greater MVC than all other groups. No differences in endurance were observed between groups. Training for climbing and participation may result in muscular adaptations.
2003	Watts et al	To describe the general anthropometric characteristics of junior USA competitive rock climbers.	Young competitive climbers have similar anthropometric characteristics to those seen in adult elite rock climbers.
2006	Espana-Romero et al	To analyse performance, anthropometric and muscle strength characteristics in elite Spanish rock climbers (n=23).	Findings suggest that the results of the Spanish climbers show a high performance level similar to that seen in World Cup climbers.
2009	Espana-Romero et al	A comparison of body fat measurement and equations in elite rock climbers (n=10).	Out of the 17 equations studied, Durnins equation was the most accurate in estimating body fat percentage.
2009	Michailov et al	To determine the anthropometric profiles of elite World Cup boulderers (n=18m/7f).	Boulders had greater body fat percentage and a greater hand strength than that seen in elite sport climbers. Other anthropometric characteristics were similar.
2011	Cheung et al	To examine the anthropometric and physiological profiles of elite Chinese sport climbers (n=11m, 10f).	Compared to national Chinese statistics, the elite climbers had a lower body mass, BMI, body fat percentage and hand grip strength.
2011	Macdonald & Callender	To characterize the athletic profile of highly accomplished boulderers (n=12).	Handgrip and finger strength was better than non-climbers and previously reported elite climbers. Boulderers body composition and core endurance was relatively similar to the control group.
2011	Tomaszewski et al	To describe competitive sport climbers with a range of abilities (6b-8c), (n=21) as well as non-climbers (n=165).	No significant differences were found between groups for body mass, height, percentage body fat or BMI. Authors questioned whether a certain anthropometric type does denote an elite level of climbing ability.

As can be seen from Table 3.3, it was not until several years after Watts et al. (1993b) researched World Cup climbers that the first European study focusing on the anthropometric characteristics of rock climbers was conducted. Grant et al. (1996) described the anthropometric, strength, endurance and flexibility characteristics of male non-climbers (n = 10, physically active), recreational climbers (n = 10 climbing a UK traditional grade of Moderate to Severe) and elite climbers (n = 10, climbing a UK traditional grade of E1 – E9). The authors reported on the bent-arm hang, sit and reach test, pull-up test and all characteristics previously described by Watts et al. (1993b). The author's findings were similar to those of Watts et al. (1993b). Grant et al. (1996) suggested that elite climbers had greater shoulder girdle endurance as well as finger strength and hip flexibility, compared to both recreational and non-climbers. The authors concluded that those climbers who aspired to climb a UK traditional grade of E1 should consider training programs that enhance performance in all the pre-defined areas. However, it was not understood whether these attributes were a pre requisite of a high standard of climbing or if they were merely advantageous.

Since these two initial studies, authors have attempted to investigate anthropometric characteristics in: male and female rock climbers who have a variety of skill levels (12-30 Ewbank) (Mermier et al., 2000), female non-climbers (active), recreational climbers (up to a UK traditional grade of Severe) and elite climbers (up to a UK traditional grade of Hard Severe) (Grant et al., 2001), and climbing specific finger endurance in intermediate rock climbers (grade 18 Ewbank and over), rowers and aerobically trained individuals (Grant et al., 2003). As competitive rock climbing grew in popularity, and competing youth categories were added by the UIAA, anthropometric studies began to mimic the pattern seen in adults. Watts et al. (2003) produced the first article describing the anthropometry of young competitive sport climbers. The authors concluded that young competitive rock climbers had similar anthropometric characteristics to their elite adult counterparts. These included a relatively small stature, low body mass, low sum of skin folds and high handgrip to mass ratio.

More recently, attention has focused on expanding the anthropometric knowledge in a range of climbers from different ethnic backgrounds and disciplines. Studies have focused on climbers from Spain (España-Romero, Ortega Porcel, García-Artero, Ruiz, & Gutiérrez Sainz, 2006) and China (Cheung et al., 2011), as well as the discipline of bouldering (Macdonald & Callender, 2011; Michailov et al., 2009). España-Romero et



al. (2006) reported that hand grip strength, body fat percentage, free fatty mass, height, weight and ability level of elite (average grade of 32 Ewbank) Spanish climbers were similar to those seen in international World Cups. However, Cheung et al. (2011) reported that elite male (average grade of 29 Ewbank) and female (average grade of 27 Ewbank) Chinese rock climbers had a smaller body size and a lower aerobic capacity than their Western counterparts. However, body fat percentage, body mass index (BMI) handgrip strength-to-weight ratio, and leg span were all similar. Both studies which investigated elite and world class boulderers (red-point average of 25 (~V 8) and 33 (~V 15) Ewbank respectively) suggested that they had stronger grip strength and a higher body fat percentage than sport climbers (Macdonald & Callender, 2011; Michailov et al., 2009).

The previously discussed studies provided a firm base of knowledge which describe in detail the anthropometric, and flexibility characteristics of a wide range of climbers. With these characteristics becoming better defined and understood, a more in-depth focus was placed on more specific possible determinants of climbing performance such as grip strength.

### **3.6 Grip strength**

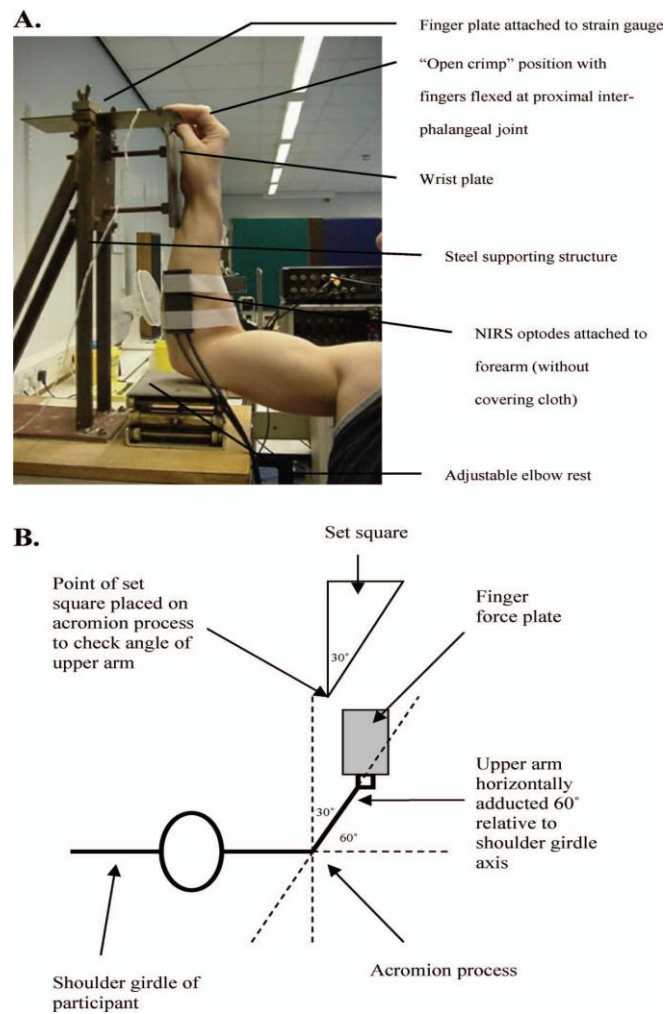
Grip strength has been suggested to be one of the most notable fatiguing factors associated with rock climbing performance (Schöffl & Kuepper, 2006; Schöffl & Schöffl, 2006; Wall et al., 2004).

#### **3.6.1 *Difficulties with measuring grip strength***

Although previous studies investigated grip strength in rock climbers, many of these used techniques which were not physiologically appropriate within their methodologies. Watts et al. (1993b) used a Jaymar hydraulic handgrip dynamometer, which was adjusted to fit each participant's hand. However, hand grip dynamometry (HGD) measures closed overall handgrip strength (from the 3<sup>rd</sup> knuckle), and not climbing specific grip strength, which is strength generated from the distal parts of the fingers. The HGD method was also used by Grant et al. (1996), Mermier et al. (2000), Watts,

Newbury, and Sulentic (1996), Giles et al. (2006) and Grant et al. (2003). In all of the studies performed by Grant et al, pincer strength was also recorded. This was done by adjusting the hand grip dynamometer to 4.5cm, and the contraction used only the thumb and forefinger. This method of measuring grip strength is considered only marginally better than HGD. However, the authors also developed a device which aimed to better represent sport specific grip strength. The device consisted of a horizontal plate which was displaced when force from the fingertips was applied to it. This plate was attached to a strain gauge which then measured finger strength.

It was later suggested that in practice, HGD does not accurately represent the form of contraction seen in the sport of rock climbing (Watts, 2004). Watts et al. (2008) highlighted this lack of sport specificity when investigating forearm electromyography (EMG) responses during both rock climbing and HGD. The authors reported significantly higher EMG readings during all climbing contractions, leading the authors to conclude that HGD lacks specificity to rock climbing. Strangely, a simple but effective approach to solving this problem was described much earlier by Köstermeyer and Weineck (1995). The method was later evaluated by Schöffl, Möckel, Köstermeyer, Roloff, and Küpper (2005) and was subsequently used by Michailov et al. (2009). The authors suggested that the athlete stands on electronic scales with the required fingers on a climbing hold. The athlete then transferred their body weight from the scales to the hold, and the difference in weight was measured. This method appears to be rudimentary, yet more sport specific than HGD when assessing the contractile strength of the forearm flexors. MacLeod et al. (2007) created an excellent sport specific measure which assessed purely open crimp grip strength in rock climbers (Figure 3.4). The authors worked with the engineering department at Glasgow University to create a force plate, which closely represented the mechanical conditions experienced on a rock climbing wall.



**Figure 3.4 Fingerboard apparatus developed by MacLeod et al., (2007).**

The apparatus was used to assess climbing specific finger endurance in sport rock climbers. The authors also assessed de-oxygenation during a sustained contraction and re-oxygenation during intermittent contractions in intermediate climbers and non-climbers. Following the work of MacLeod et al. (2007), the testing apparatus was reproduced by Philippe, Wegst, Müller, Raschner, and Burtscher (2011) who investigated climbing specific finger flexor performance, and forearm muscle oxygenation in elite male and female sport climbers. These latest studies show how assessments of performance related grip strength have become more sport specific, and therefore more relevant and representative. However, there remains a need to more accurately assess the haemodynamic changes associated with grip strength in a range of climbing ability groups.

### **3.6.2 Development of grip strength and endurance research**

Grip strength has been a focal point of interest for some time. Cutts and Bollen (1993) were the first known authors to investigate grip strength and endurance in rock climbers. They examined whether forearm flexors were stronger in rock climbers compared to non-climbers, and consequently whether this was a possible predisposition for injuries within the sport. The study investigated HGD and pincer grip strength in 13 climbers and 12 non-climbers. The climbing group performed significantly better in both tests. However, there were no correlations between the handgrip data and climbing grade. The lack of a correlation could be due to the use of HGD and its lack of specificity to the sport (MacLeod et al., 2007; Michailov et al., 2009; Watts et al., 2008). Watts et al. (1996) used a similar method to understand handgrip fatigue during difficult climbing, and the subsequent recovery time course. Climbers were asked to ascend a difficult pre-practised route; HGD and blood lactate (BLa) levels were sampled 10 minute pre-climb, immediately post-climb and during 5, 10 and 20 minute of recovery. Handgrip strength decreased by 22%. However, endurance (handgrip strength saw a much larger decrease (57%) between pre and post-climb, whilst BLa rose from  $1.4 \pm 0.8$  to  $6.1 \pm 1.4$  mmol·L<sup>-1</sup>. Blood lactate, strength nor endurance fully recovered within the 20 minute recovery period, and consequently the authors reported that handgrip strength recovers at a faster rate than handgrip endurance.

After the initial work of Cutts and Bollen (1993), and Watts et al. (1996) there appears to be a considerable break in the literature. It was not until several years later that handgrip strength was revisited. From 2003 to 2012 there are eleven known studies that focused specifically on the characteristics of forearm flexor and handgrip strength in rock climbers. These studies can be broken down into two investigative areas:

- 1) Those that have attempted to assess the finger and forearm characteristics of climbers versus non-climbers, within a variety of testing scenarios including assessing: EMG finger flexor fatigue (Quaine et al., 2003), assessing de-oxygenation during sustained and intermittent contractions (MacLeod et al., 2007), describing the effects of climbing specific finger endurance on climbers, non-climbers and rowers (Grant et al., 2003).
- 2) Studies that have investigated grip strength and forearm flexors from a performance perspective including: climbing-specific finger flexor performance and forearm muscle oxygenation characteristics in elite male and female climbers (Philippe et al., 2011), development of performance diagnosis of the anaerobic strength and endurance of the

forearm flexor muscles in sport climbers (Schöffl et al., 2005), correlating forearm strength and sport climbing performance (Schweizer et al., 2007), and the effect of hold depth and grip technique on maximal finger forces in climbing (Amca, Vigouroux, Aritan, & Berton, 2012).

Overall the research into handgrip and finger flexor performance appears to be relatively inconsistent. This inconsistency could potentially be due to the large range of protocols and variation in participants used within the studies. Current findings appear to suggest that: 1) the use of HGD is not representative of the grip strength used in rock climbing (Schöffl et al., 2005; Watts et al., 2008), 2) climbers appear to have better strength but not necessarily endurance compared to non-climbers (Grant et al., 2003), and 3) forearm and grip strength does not necessarily correlate to a performance grade in climbers (Philippe et al., 2011; Schweizer et al., 2007). It is clear that a greater understanding is required of 'grip strength and forearm flexor performance', two of the most influential aspects of climbing performance. Although some aspects of grip strength, particularly methods of assessment are becoming more clearly understood, a greater knowledge of the interactions of associated physiological systems that effect sport specific grip strength is required. This is of particular interest as grip strength has been suggested to be one of the most important and trainable areas of a climbers performance (Horst, 2008).

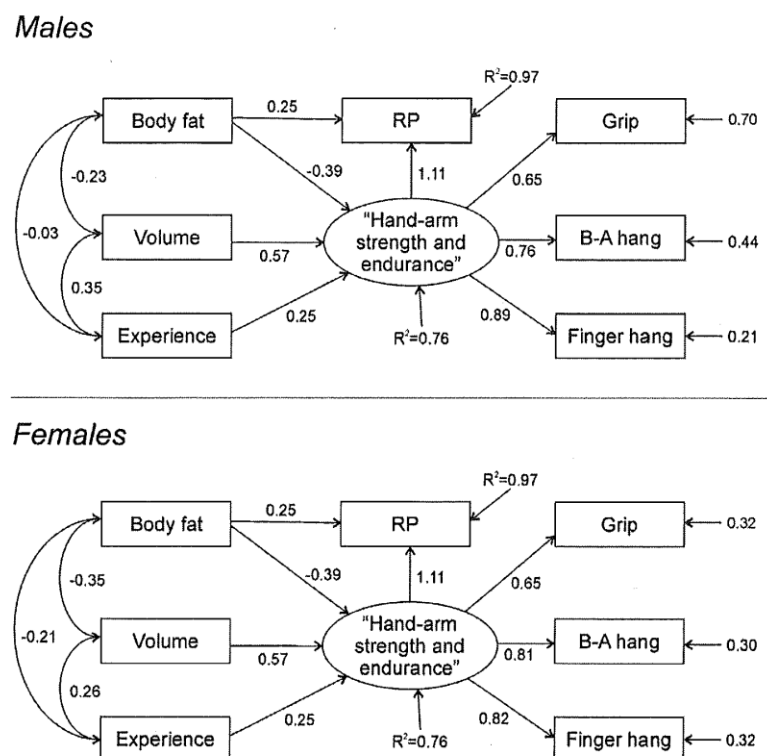
### **3.7 Performance prediction and assessment tools**

Specificity in training and testing has become a well-established concept. As previously mentioned, there has been some description of what physiological and anthropometric measurements separate climbers from non-climbers in both sport climbing and bouldering (España-Romero et al., 2006; Macdonald & Callender, 2011; Michailov et al., 2009). However, there has been relatively little research that aims to distinguish the differences between rock climbers of different abilities. This could be in part a reason for the lack of research not only into specific training guidelines in rock climbing, but also the very limited body of research that aims to predict climbing performance.

Several studies have attempted to predict climbing performance whilst investigating other physiological and anthropometric aspects of the sport (Mermier et al., 2000; Watts et al., 1993b). The earliest known study where the sole aim was to try and predict climbing performance was in 2004 (Wall et al., 2004). Considering the suggested ‘birth’ of the sport was in the 1880’s, this seems quite a late attempt to start to predict performance and understand forms of climbing assessment. Since Wall et al. (2004), there has only been six known peer reviewed studies, of which five have attempted to either develop a performance assessment tool (Bertuzzi et al., 2012; Brent et al., 2009; Draper et al., 2009), or use overall climbing measures to predict performance (Baláš et al., 2012; Wall et al., 2004). The sixth study placed much emphasis on the pedagogical aspects of climbing and not performance based sport science. The study was aimed at physical education teachers who could use rock climbing as a tool for expressing the use of performance cues in beginner climbers (McNamee & Steffen, 2007).

With a sports science focus, Wall et al. (2004) were the first to attempt to understand whether the strength characteristics of rock climbers could be used to predict performance. The study used only female climbers and subdivided them into three ability groups: moderate (16-18 Ewbank,  $n = 6$ ), intermediate (18-21 Ewbank,  $n = 6$ ) and expert (21-24 Ewbank,  $n = 6$ ). Participants were tested over a three day period and measurements of both bouldering and route climbing (top rope) performance were noted as well as anthropometric, climbing specific strength, and flexibility characteristics. When expressed as strength-to-weight ratio, there were significant differences ( $p < 0.05$ ) between the ability groups for climbing specific handgrip strength and one-arm lock off strength. Furthermore, these two variables were significantly correlated ( $p < 0.05$ ,  $R^2 = 0.426$ ) to their indoor climbing performance grades. However, as would be expected, scores for a ‘previous climbing experience questionnaire’ appeared to have a stronger significant correlation to indoor climbing performance ( $p < 0.05$ ,  $R^2 = 0.86$ ). The authors concluded that the climbing specific handgrip strength, as well as one-arm lock off strength were sensitive, accurate measures of climbing specific performance. Furthermore, these variables were suggested to be accurate tools for the prediction of indoor rock climbing performance. However,  $R^2 = 0.426$  is generally considered a moderate correlation at best (Boslaugh & Watters, 2008), and it could be argued that the physiological variables here may not be particularly strong predictors of climbing performance.

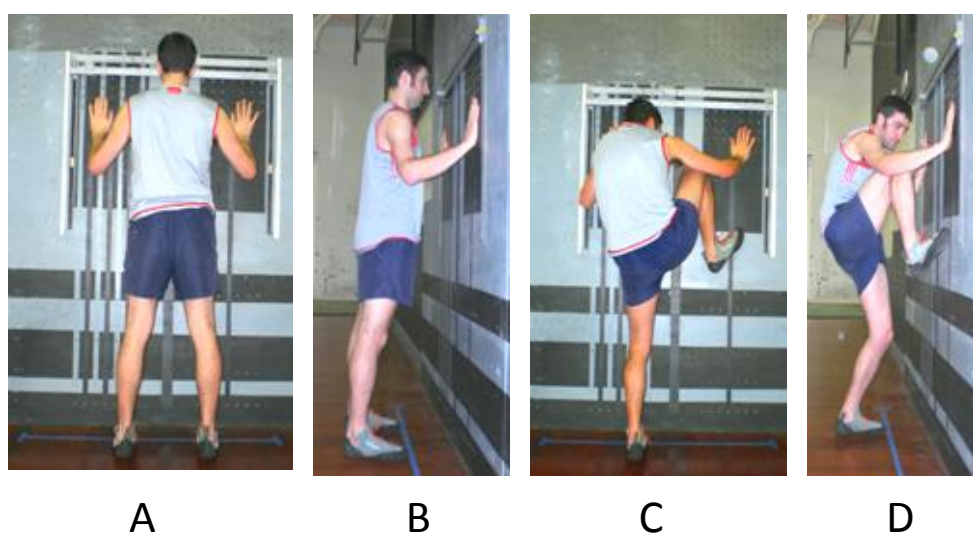
Baláš et al. (2012) showed similarly moderate to strong correlations between grip strength related to body mass ratio, and red-point grade ( $R^2 = 0.3_{\text{male}}, 0.57_{\text{female}}$ ). However, stronger correlations were reported between red-point grade and the finger hang (s) ( $R^2 = 0.76_{\text{male}}, 0.66_{\text{female}}$ ) as well as bent-arm hang (s) ( $R^2 = 0.49_{\text{male}}, 0.64_{\text{female}}$ ). A particularly weak correlation was reported between years of climbing experience, and red-point grade ( $R^2 = 0.23_{\text{male}}, 0.37_{\text{female}}$ ). Yet this is not surprising as many recreational climbers are known to have extremely high levels of experience, but have a low technical ability as they may only climb once or twice a month, but may have been doing so for many years. Although the individual correlations within the work of Baláš et al. (2012) were a mixture of weak to strong  $R$  values, a novel approach of the study design was using multiple linear regression to explain 86% (male) and 85% (female) of the variance in red-point performance. Furthermore, as these variables were suggested to have strong correlations to strength and endurance tests. The authors used the latent variable hand-arm strength and endurance, as a mediator to express their relationship with red-point performance. Using the model the authors were able to explain 97% of the variance in climbing performance as shown within Figure 3.5.



**Figure 3.5 Standardised solution of two-group full structural model. Numerical values belong to the single-headed, and double-headed arrows represent standardisation path coefficients, respectively (Baláš et al., 2012).**

The authors suggested that the combined training characteristics have a close relationship with climbing specific strength, and that this was a good indicator of climbing performance. It is clear though from the findings of Baláš et al. (2012) that individual sport specific measures of climbing performance do not alone predict overall climbing performance. It is quite apparent that rock climbing performance is made up from a plethora of different characteristics including but not limited to: sport specific strength, anthropometric, biomechanical and psychological components; all of which alter an individual climber's performance to a particular degree.

In order to continue trying to investigate specific training and performance tools within rock climbing, several authors attempted to develop performance assessment tools that focused on other areas: specific rock climbing moves (Brent et al., 2009), flexibility tests (Draper et al., 2009) and climbing fit tests (Bertuzzi et al., 2012). Brent et al. (2009) investigated the use of a rock climbing specific move called a 'rock-over', as a way of monitoring climbing performance. The authors designed a specific rig which was based on a 90° climbing wall. Climbers of a range of ability levels were asked to rock-over on adjustable foot and hand holds, and reach as high as they could with their hand (dominant side only, A-D in Figure 3.6). This maximised sport specificity as the climber not only used actual climbing holds, but the movement required unique flexibility in the hips and arms, as well as the drive of the legs and pull of the arms to propel the climber vertically up the wall as shown in Figure 3.6.



**Figure 3.6 Sequence used during the rock-over climbing test (Brent et al., 2009).**



The data showed there was a significant relationship between scaled (to the height of the climber) rock-over scores and climbing ability ( $R^2 = 0.67$ ,  $p < 0.0005$ ). Regression modelling from the rock-over explained 45% of the variance in scores between climbers. As a percentage of participant height, rock-over scores for novice, intermediate, advanced and elite climbers were 59.5%, 71%, 82% and 90% respectively. Furthermore, these differences were found to be significant ( $p < 0.0005$ ). The authors suggested that the rock-over was a reliable and useful measure of climbing performance. In a similar study Draper et al. (2009) investigated the use of flexibility assessment tools as a performance measure. The authors had climbers of different abilities perform four tests on a purpose built climbaflex board; the adapted Grant foot raise, climbing specific foot raise, lateral foot reach and the foot-loading flexibility test. The climbers were also asked to perform two existing measures of flexibility, the Grant foot raise and the sit and reach test. Both these tests were shown to have poor correlations with climbing performance. The lateral foot reach and the adapted Grant raise were shown to have weak correlations with performance grades ( $R^2 = 0.30$ ;  $R^2 = 0.34$ ). The foot-loading flexibility test had the strongest correlation with performance ( $R^2 = 0.65$ ). The authors concluded that the foot loading test was a valid and reliable measure which assessed the ability of climbers to use an extreme range of hip flexibility in a rock-over style move.

Most recently Bertuzzi et al. (2012) developed an indoor rock climbing test to assess overall sport specific climbing fitness. The test involved both elite ( $n = 6$ ) and recreational ( $n = 7$ ) climbers ascending and descending a 10m route as fast as possible. Oxygen consumption and HR were measured using a K4b<sup>2</sup> breath-by-breath metabolic system, and BLa and handgrip strength were measured pre and post-test. The authors reported significant differences between the groups for the number of moves performed within the three minute climb period. Handgrip strength was significantly ( $p < 0.05$ ) higher in the elite group both pre and post-climb. There were no other significant differences reported. However, as the total number of climbing moves was significantly higher in the elite group, the O<sub>2</sub> cost per move was smaller and significantly lower ( $p < 0.05$ ) than the recreational group. As the intraclass correlation coefficient between the two test performances was 0.97, it was concluded that the test was a reliable one, and could be an alternative accurate 'fit-climbing test'. Although the study had revealed some interesting findings it must be mentioned that the style of climbing (down climbing) is not representative of indoor rock climbing. Although down climbing was

used to prevent passive recovery, this style of climbing is not common place. The unfamiliar eccentric muscle contraction could affect the overall energy cost of the route. The use of a treadwall may have prevented some of these issues.

### **3.8 Physiological demands of rock climbing**

Prior to physiological training guidelines being created for any given sport, an understanding of the physiological demands needs to be understood first. Early research sought to investigate efficiency within sport rock climbing (Rushworth, 1972), and observe the physiological effects of different ascents and styles (Billat, Pallega, Charlaix, Rizzardo, & Janel, 1995; Mermier, Robergs, McMinn, & Heyward, 1997; Williams, Taggart, & Carruthers, 1978). However, unlike sports such as running and cycling, rock climbing is incredibly difficult to standardise in either a laboratory or field based environment. Almost every aspect of the sport from the route to the performer is unique. Consequently, the climbers' style is often different within each ascent, even if the route remains the same. It is extremely difficult to define the natural ascent style of a specific ability group of climbers due to the number of uncontrollable variables within the group. Variables such as height, weight, limb lengths and flexibility have such large affects on the way in which an individual approaches and ascends a climb. Furthermore, the psychological way in which climbers approach and perceive a route, and each route style (slab, overhang or vertical) may also often be different. Consequently, this range of uncontrollable variables may affect the physiological demands placed on each climber in a different way. These non-homogenous and uncontrollable variables create notable standardisation problems for researchers who are trying to define the purely physiological demands of climbing.

Over the past three decades there has been a large number of studies which have sought to investigate the physiological responses of rock climbing under a number of different conditions, ascent styles and disciplines. Researchers have gathered information which highlights O<sub>2</sub> consumption and HR responses (Billat et al., 1995; Mermier et al., 1997), BLa responses (Booth, Marino, Hill, & Gwinn, 1999; Draper et al., 2008; Watts & Drobish, 1998), energy system contributions (Booth et al., 1999; Pires, Hammond, Lima-Silva, Bertuzzi, & Kiss, 2011a; Rodio, Fattorini, Rosponi, Quattrini, & Marchetti, 2008), energy expenditure (EE) (Bertuzzi, Franchini, Kokubun, & Kiss, 2007; Rosponi,

Schena, Leonardi, & Tosi, 2012; Sell, Clocksin, Spierer, & Ghigiarelli, 2011) and the hormonal responses to the sport (Cesur, Atay, Ogut, Polat, & Ongel, 2012; Magalhães et al., 2007; Merrells, Friel, Knaus, & Suh, 2008b; Sherk, Sherk, Kim, Young, & Bembien, 2011; Williams et al., 1978). The following subsection 'Physiological demands of rock climbing' aims to describe the research within these areas to date, and critically analyze both the relevance and significance of each authors work.

### **3.8.1 *Oxygen uptake and heart rate responses***

There has been much development in the assessment of O<sub>2</sub> uptake and HR responses in rock climbing over the last two decades. Studying the physiological demands of rock climbing started in the late 1970's. The preliminary research used HR monitors and Douglas bags which were hauled up rock faces. One of the earliest known studies to assess the physiological demands in climbers was by Williams et al. (1978). The authors investigated the use of beta-blockers (oxprenolol) on both the HR and catecholamine responses during rock climbing. Although O<sub>2</sub> uptake was not measured, the aim of the study was to determine the extent of both the physical and emotional (anxiety) stresses during the sport. The participants completed an outdoor climb (top rope) after the ingestion of a placebo tablet, and then again after the ingestion of a beta-blocker (oxprenolol). The mean HR was significantly ( $p < 0.05$ ) lower on the second ascent ( $166 \pm 20$  and  $120 \pm 10$   $\text{bts} \cdot \text{min}^{-1}$  respectively). Plasma adrenaline concentration significantly increased ( $p = 0.001$ ) from 0.05 to  $0.33 \mu\text{g} \cdot \text{L}$  after the placebo trial, but no significant differences were observed after climbing with beta-blockers. It was suggested that rock climbing represents more of an anxiety stress rather than a physical stress and as such is likely to increase moral fibre rather than physical fibre (Williams et al., 1978). Although this study had a number of methodological errors, it was an interesting starting point for research into the 'physiological demands of rock climbing'.

Billat et al. (1995) were the first to measure the volume of oxygen ( $\dot{V} \text{O}_2$ ) and HR responses in a small number ( $n = 4$ ) of rock climbers, with the intention of determining which was the predominant energy system. The authors measured the  $\dot{V} \text{O}_2$ , HR and BLa, and used video analysis to assess four climbers during two lead climbs of differing grades (grade 25 and a grade 25 (Ewbank) which was steeper), and a maximal arm pull

test. Billat et al. (1995) were the first authors to report a disproportionate rise in  $\dot{V}O_2$  over the associated HR during rock climbing. The authors found that during the ascent, climbers reached only 46 and 37.5% of their treadmill  $\dot{V}O_{2max}$ , yet HR reached 85.5 and 84% respectively. However, when the climbing data is compared to maximal arm crank and not whole body treadmill exercise, the values seen during climbs of 25 and steeper 25 (Ewbank) are far greater for both  $\dot{V}O_2$  and HR (113%  $\dot{V}O_{2max}$ , 93% HR max: 95%  $\dot{V}O_{2max}$ , 84% HR max respectively). The authors concluded that rock climbing does not imply an oxidative metabolism due to the low percentage of treadmill maximum  $O_2$  uptake ( $\dot{V}O_{2max}$ ) used. It was reported that a higher  $\dot{V}O_2$  was seen during the more technical climb of 25 (Ewbank) (45.6% of treadmill max) compared to the steeper climb which was also graded 25 Ewbank (37.7% of treadmill max), and yet the authors suggested that the oxidative metabolism appeared to be more important during the steeper sections of a route. It should be noted that the  $\dot{V}O_2$  data was only from the last half of each route and was collected via Douglas bags which were hauled up the route next to each participant.

Since Billat et al. (1995) first measured these low percentages of treadmill  $\dot{V}O_{2max}$  used during rock climbing, several studies have reported similar findings with both treadmill and cycle ergometry (de Geus, Villanueva O'Driscoll, & Meeusen, 2006; Draper et al., 2008; Mermier et al., 2000; Rodio et al., 2008; Rosponi et al., 2012; Sheel, 2003). As shown in Table 3.4, Table 3.5 and Table 3.6, these studies have generally reported that rock climbing appears to elicit a higher percentage of maximal cycle ergometry for both  $\dot{V}O_2$  and HR compared to treadmill running. This is most likely due to the lower  $\dot{V}O_{2max}$  values often seen during cycle ergometry compared to treadmill running (Sheel, 2004). When measuring HR and whole body  $\dot{V}O_2$ , treadmill running uses a greater muscle mass and is more dynamic in nature, eliciting higher maximal responses than cycling.



**Table 3.4 Oxygen uptake during all known major rock climbing studies (Grades converted to Ewbank using Draper et al. (2011) Appendix G).**

Study	Ability definition (Ewbank)	Condition/route (Ewbank)	Route practise	Duration s (± SD)	Average $\dot{V} O_2$ mL·kg <sup>-1</sup> ·min <sup>-1</sup> (± SD)	$\dot{V} O_{2peak}$ mL·kg <sup>-1</sup> ·min <sup>-1</sup> (± SD)	% of bike/run/treadwall $\dot{V} O_{2max}$ (± SD)	% of arm $\dot{V} O_{2max}$ (± SD)	EE (± SD)
Billat et al., (1995)	High level (3 years experience)	Lead (25)	5 hours on route	210 - 240	24.9 (1.2)	NR	46 (4.9)	113 (12.6)	NR
		Lead (25 considered harder)		210 - 240	20.6 (0.9)	NR	37.5 (5.4)	95.6 (6.2)	NR
Mermier et al., (1997)	Experienced (NR)	TR (12) at 90°	NR	300	20.7 (8.1)	NR	NR	NA	0.149 kcal·kg·min <sup>-1</sup>
		TR (17) at 106°	NR	300	21.9 (5.3)	NR	NR	NA	0.159 kcal·kg·min <sup>-1</sup>
		TR (21) at 151°	NR	300	24.9 (4.9)	NR	NR	NA	0.202 kcal·kg·min <sup>-1</sup>
Watts & Drobish (1998)	Experienced (basic course)	TW (14) at 80°	Familiarisation climb	240	31.3 (4)	NR	NR	NR	11 (2.3) kcal·min <sup>-1</sup>
		88°		240	31.7 (4.6)	NR	NA	NA	11.2 (2.8) kcal·min <sup>-1</sup>
		91°		240	31.2 (4.6)	NR	NA	NA	11 (2.2) kcal·min <sup>-1</sup>
		96°		240	29.5 (5.2)	NR	NA	NA	10.4 (2.5) kcal·min <sup>-1</sup>
		102°		240	30.9 (3.7)	NR	NA	NA	10.9 (2) kcal·min <sup>-1</sup>
Booth et al., (1999)	Elite (OS 19-25)	TW	Familiarisation	446.4	NR	43.8 (2.2)	NA	NA	NR
		OL (18)	Pre-practised	441.6	NR	32.8 (2)	75 (4)	NA	NA
Watts et al., (2000)	Experienced (RP 26 – 33)	Lead (25)	Pre-practised	177 (41)	24.7 (4.3)	31.9 (5.3)	NA	NA	NR
Sheet at al., (2003)	Elite (>2 yrs competition)	TR Easy climbing (19)	Familiar	90 - 210	20.1 (3.3)	NR	66.9	NA	NR
		TR Hard climbing (23)	Familiar	90 - 210	22.7 (3.7)	NR	89.6	NA	NR
de Gues et al., (2006)	Expert (OS 25 – 27)	TR (27) at 120 -135°	Pre-practised	189 (25)	35.9 (3.2)	41.62 (4.19)	69.6 (7.3)	NA	NR
		TR (27) at 90°	Pre-practised	244 (38)	35.9 (3.6)	44.1 (5.82)	68 (10.6)	NA	NR
		Traverse (27) at 135-180°	Pre-practised	190 (68)	34.9 (3.1)	40.5 (4.36)	65.9 (9.9)	NA	NR
		Traverse (27) at 90°	Pre-practised	195 (51)	32 (3.8)	39.14 (5.38)	60.8 (9.8)	NA	NR
Bertuzzi et al., (2007)	Recreational (climb>23)	TR Easy (18) at 90°	Pre-practised	83.9 (20.1)	30.3 (7.7)	30.6 (5.5)	NA	104.3 (27.7)	23.19 (4.51) kcal
	Elite (top 10 national ranking)	TR Easy (18) at 90°	Pre-practised	73.8 (17.6)	23 (5.2)	37.2 (7.6)	NA	102.2 (19.5)	17.05 (2.32) kcal
	Elite (top 10 national ranking)	TR Moderate (22) at 120°	Pre-practised	80.8 (145.5)	30.1 (6.9)	38 (6.3)	NA	106.4 (23.9)	19.35 (3.08) kcal
	Elite (top 10 national ranking)	TR Difficult (25) at 110°	Pre-practised	82.3 (16.4)	31.3 (8)	38.6 (5.4)	NA	108.1 (24.8)	21.99 (3.68) kcal

Study	Ability definition (Ewbank)	Condition/route (Ewbank)	Route practise	Duration s ( $\pm$ SD)	Average $\dot{V} O_2$ mL·kg <sup>-1</sup> ·min <sup>-1</sup> ( $\pm$ SD)	$\dot{V} O_{2peak}$ mL·kg <sup>-1</sup> ·min <sup>-1</sup> ( $\pm$ SD)	% of bike/run/treadwall $\dot{V} O_{2max}$ ( $\pm$ SD)	% of arm $\dot{V} O_{2max}$ ( $\pm$ SD)	EE ( $\pm$ SD)
Rodio et al., (2008)	Recreational male (16 – 23)	TR (14)	NR	420 (120)	28.3 (1.5)	39.1 (4.3)	70 (6)	NA	~9.8 kcal·kg <sup>-1</sup> (70kg person)
	Recreational female (16 – 23)		NR	660 (180)	27.5 (3.6)	39.7 (5)	72 (8)	NA	
Draper et al., (2008)	Intermediate (14 – 15 traditional)	OS sport lead (17)	OS	213 (46)	26.54 (2.46)	NR	46	NA	NR
		2 <sup>nd</sup> sport lead (17)	2 <sup>nd</sup> Lead	199 (33)	25.98 (2.48)	NR	45	NA	NR
Draper et al., (2010)	Intermediate (sport 19-22)	TR (19)	OS	87 (22)	25.1 (1.3)	38.29 (5.92)	42	NA	NR
		Lead (19)	OS	193 (30)	25.9 (2.6)	40.87 (6.63)	44	NA	NR
Romero et al., (2011)	Experienced (21–25)	TR week 1 (18)	Pre-practised	122 (36)	NR	36.9 (4.9)	NA	NA	17 (5.1) kcal
		TR week 4 (18)	Pre-practised	116 (36)	NR	36 (5.2)	NA	NA	14.6 (5) kcal
		TR week 6 (18)	Pre-practised	110 (24)	NR	36.1 (3.7)	NA	NA	13.2 (4.5) kcal
		TR week 9 (18)	Pre-practised	98 (18)	NR	36.8 (3.7)	NA	NA	11.5 (3.2) kcal
Bertuzzi et al., (2012)	Elite (>26)	TR (18)	OS	NR	NR	51.76 (7.28)	NA	NA	NR
	Recreational (23)	TR (18)	OS	NR	NR	47.69 (8.88)	NA	NA	NR
Rosponi et al., (2012)	Skilled climbers (25 – 29 OS)	TR (19) Self selected pace(SS)	NR	~300	35.9 (6.7)	NR	NR	NA	16.79 (1.12) kcal·kg <sup>-1</sup> ·min <sup>-1</sup>
		TR (19) 50% lower than self selected pace	NR	~300	28.3 (7.4)	NR	NR		21.57 (1.12) kcal·kg <sup>-1</sup> ·min <sup>-1</sup>
		TR (19) 50% higher than self selected pace	NR	~300	43.9 (6)	NR	NR		13.23 (3.15) kcal·kg <sup>-1</sup> ·min <sup>-1</sup>

EE = energy expenditure, TR = top rope, OS = on-sight, RP = red-point, NR = not reported, NA = not applicable, OL = Outdoor lead, TW = Treadwall

Mermier et al. (1997) sought to quantify the physiological responses of experienced male ( $n = 9$ ) and female ( $n = 5$ ) rock climbers during three increasingly difficult top roped (12, 16 & 21+ Ewbank) climbs. The authors reported similar  $\dot{V}O_2$  percentages as Billat et al. (1995). However, Mermier et al. (1997) used predicted maximum values instead of an actual maximal exercise test. The authors reported that as the difficulty/steepness of the route increased (became more overhung), so did the  $\dot{V}O_2$  consumption, but these were only marginal increases (20.7, 21.9 and 24.9 mL·kg<sup>-1</sup>·min<sup>-1</sup> respectively). However, as the difficulty increased, the elevation in HR was much larger (142, 155 & 163 bts·min<sup>-1</sup>). The authors attributed this disproportionate rise in HR and  $\dot{V}O_2$  to the amount of isometric contraction that would have taken place. It has been well documented that isometric contraction of the forearms elicit a high HR during HGD without a corresponding elevation in  $\dot{V}O_2$  (Cornett et al., 2000; O'Leary, 1993; West, Hicks, Clements, & Dowling, 1995). Furthermore, Billat et al. (1995) had previously suggested that isometric time was up to one third of total climb time, which in part may explain the disproportionate rise in HR. However, isometric contraction was defined as the period when the climber's hips were not in motion. Unfortunately, this definition does not account for any period of time which the climber might have spent resting their hands or fingers for on route recovery.

Assessment of the  $\dot{V}O_2$  responses during rock climbing has been vastly improved since the introduction of portable metabolic systems to measure  $O_2$  consumption in climbers. The first authors to use this method, did so not in sport climbing but in a 27 move bouldering circuit graded 24 (Ewbank) (Wilkins, Watts, & Wilcox, 1996). An Aerosport TEEM 100 (Aerosport, Ann Arbor, Michigan USA) was used to continually collect expired air during the bouldering route. Oxygen uptake averaged 20.9 mL·kg<sup>-1</sup>·min<sup>-1</sup> with a mean peak of 27.4 mL·kg<sup>-1</sup>·min<sup>-1</sup>. These values represented an average 33-38%, and a peak of 43-50% of treadmill  $\dot{V}O_{2max}$ . Since this initial study a wealth of climbing research has used portable metabolic systems, the most common being the Cosmed instruments (Cosmed, Italy) (Bertuzzi et al., 2007; Booth et al., 1999; Draper et al., 2008; Draper et al., 2010; Nicholson et al., 2007). This advance in technology has enabled studies to investigate the  $\dot{V}O_2$  responses during a number of different climbing conditions in numerous ability groups (Booth et al., 1999; Draper et al., 2010; Nicholson et al., 2007; Rodio et al., 2008).



Rock climbing is difficult to standardise, the simple dynamic nature of the sport means that even with the most controlled methods there are still uncontrollable variables which can affect and alter a performance or response. This in part was the reason for introducing the climbing-treadwall for much physiological based research. The treadwall enables close monitoring of the physiological aspects of a climber without the need to control for potential anxiety issues associated with height or fear of falling. The treadwall also allows climbers to ascend at a maximal speed until exhaustion in a more controlled environment. Unfortunately, this device does not really represent the sport as a whole, just one part of its physical demand.

Watts and Drobish (1998) were the first known authors to utilise a treadwall. Climbers who had completed a basic climbing course, ascended a route which was graded 14 (Ewbank), at an angle of 80° for a four minute period. After a rest of six minutes they were required to ascend the climb again at increasing angles (88°, 91°, 96° and 102°). The authors reported similar  $\dot{V}O_2$  responses for all angles ascended, which were similar to those reported by Mermier et al. (1997). The average  $\dot{V}O_2$  remained similar with only small fluctuations, the largest being 1.4 mL·kg<sup>-1</sup>·min<sup>-1</sup> (96° – 102°). However, HR increased with each angle until 91° where it plateaued between 171-173 bts·min<sup>-1</sup> (see Table 3.4). The study also suggested that there was a considerable difference between  $\dot{V}O_2$  during the climbing and running tests ( $30.2 \pm 4.7$  and  $36.6 \pm 5.5$  mL·kg<sup>-1</sup>·min<sup>-1</sup> respectively) when exercising at the same HR (162 bts·min<sup>-1</sup>). The authors suggested that the upper body appeared to be the primary work contributor, and that an arm-specific  $\dot{V}O_2$  may have been reached. It should be noted however, that although the cohort was reported as experienced, the pre-requisite was a ten day climbing course and therefore they should be considered beginner climbers due to a lack of climbing experience and presumably skill. The techniques that an experienced climber would have compared to one who has completed a ten day course could be large, and this may have affected the efficiency and contributions of both the lower and upper body. Numerous technique publications suggest that skilled climbers will try and use as much leg work as possible to conserve the arms, as the legs are considerably more powerful. This technique is particularly useful during overhanging sections of a route (past 90° vertical) (Goddard & Neumann, 1994; Horst, 2008). This technique is one of many that beginner climbers may not have yet learned or refined.

Booth et al. (1999) were the first authors to investigate the physiological responses in elite sport climbers. The groups were defined as being able to on-sight grade 19 – 25 (Ewbank) and should therefore be considered more advanced to elite, rather than purely elite climbers. Being able to on-sight a route graded 25 (Ewbank) is considerably harder than a grade 19 (Ewbank), consequently these different ability climbers lack homogeneity and should not be grouped within the same category. The authors measured  $\dot{V}O_2$ , HR and BLa responses during a treadwall test and a pre-practiced outdoor route graded at 18 (well below their best on-sight grade of 25). Oxygen uptake peaks were high at  $43.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  on the treadwall and  $32.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  during the outdoor climb, and HR peaks were 190 and 157  $\text{bts}\cdot\text{min}^{-1}$  respectively. The relatively low HR recorded during outdoor climbing could be due to the relative ease of the climb compared to some of the participant's best on-sight grades of 19 – 25 (Ewbank). Later studies recognised these large differences in performance grades and began to use narrower grade boundaries. For example Draper et al. (2010) had 'intermediate' climbers leading at the top of their ability on a route which was graded at 19 (Ewbank). Whereas, de Geus et al. (2006) classed 'expert' climbers as having a best on-sight of 25-27 (Ewbank). These two distinctly different ability groups (which cover the 19-25 grade boundary) used by Booth et al. (1999) were notably different and should not be classed together.

Sheel (2003) also reported low HR values ( $129 \pm 13 \text{ bts}\cdot\text{min}^{-1}$ ) when climbers were ascending on top rope routes well below their best ability level. Booth et al. (1999) reported that  $\dot{V}O_2$  responses for the outdoor climb were higher than those seen by Billat et al. (1995) and Mermier et al. (1997), but were similar to Watts and Drobish (1998) even though the route used by Booth et al. (1999) was pre-practiced and below their best on-sight grade. However, it should be noted that Booth et al. (1999) reported  $\dot{V}O_2$  peak and not  $\dot{V}O_2$  average and therefore it would be naturally higher. Furthermore, climb time was considerably longer during the study by Booth et al. (1999), 377 – 572s compared to: 210-240s (Billat et al., 1995), 300s (Mermier et al., 1997) and 240s (Watts & Drobish, 1998). This increase in climb time, blended with a relatively easy climbing route could mean that higher level performers (who on-sight nearer to grade 25 (Ewbank)) may have been able to use a more efficient style of ascent with good technique, and may have consequently used a greater aerobic contribution. The authors concluded that climbing a moderately difficult outdoor sport route requires a significant

contribution of  $\dot{V}O_2$  peak, and that the belief that aerobic fitness is not important may be untrue.

Since these initial studies investigated the physiological responses of both HR and  $\dot{V}O_2$ , the focus of research shifted. Previously the aims were to define and understand  $\dot{V}O_2$  and HR, whereas after the year 2000, studies became interested in the performance aspects of these physiological components. Focus was placed on: recovery strategies (Watts, Daggett, Gallagher, & Wilkins, 2000), differences in styles of ascent (Sheel, 2003), what separates recreational and elite performers (Bertuzzi et al., 2007), the effect of on-sight climbing (Bertuzzi et al., 2012; Draper et al., 2010), the effects of pre-practising routes (España-Romero et al., 2012) and self-selecting climbing speeds (Rosponi et al., 2012). These appear to all have a similar overall aim of advancing the knowledge and understanding of roped climbing whilst potentially seeking gains in performance.

**Table 3.5 Heart rate responses during all known major rock climbing studies (grades converted to Ewbank using Draper et al. (2011) Appendix G).**

Study	Ability definition (Ewbank)	Condition/route (Ewbank)	Route practise	Duration s (± SD)	Average HR bts·min <sup>-1</sup> (± SD)	HR <sub>peak</sub> bts·min <sup>-1</sup> (± SD)	% of bike/run/treadwall $\dot{V}O_{2max}$ HR (± SD)	% of arm $\dot{V}O_{2max}$ HR (± SD)
Williams et al., (1978)	Novice to professional	Placebo	NR	600 – 900	166 (20.4)	NR	NA	NA
		Beta blocker	NR	600 – 900	120 (10.2)	NR	NA	NA
Billat et al., (1995)	High level (3 years experience)	Lead (25)	5 hours on route	210 – 240	176 (140)	NR	85.5 (3.2)	93 (5.5)
		Lead (25+)		210 – 240	159 (14.7)	NR	84 (6.6)	84 (6.6)
Mermier et al., (1997)	Experienced (Not reported)	TR (12) at 90°	NR	300	142 (19)	NR	74 – 84% of predicted max	NA
		TR (16) at 106°	NR	300	155 (15)	NR	74 – 84% of predicted max	NA
		TR (21) at 151°	NR	300	163 (15)	NR	74 – 84% of predicted max	NA
Ferguson & Brown (1997)	Elite (23 – 30)	Sustained hand grip exercise	NA	140 (11.1)	113 (14)	NR	NA	NA
	Sedentary	Sustained hand grip exercise	NA	122 (14.2)	98 (5)	NR	NA	NA
	Elite (23 – 30)	Intermittent hand grip exercise	NA	853 (75.6)	84 (1)	NR	NA	NA
	Sedentary	Intermittent hand grip exercise	NA	420 (68.9)	107 (4)	NR	NA	NA
Watts & Drobish (1998)	Experienced (basic course)	Treadwall (14) at 80°	Familiarisation climb	240	156 (17)	NR	NA	NA
		88°		240	165 (16)	NR	NA	NA
		91°		240	171 (17)	NR	NA	NA
		96°		240	173 (15)	NR	NA	NA
		102°		240	171 (16)	NR	NA	NA
Booth et al., (1999)	Elite (OS 19 – 25)	Treadwall	Familiarisation	446.4	NR	190 (4)	NA	NA
		Outdoor (18) lead	Pre-practised	441.6	NR	157 (8)	83 (4) % of peak	NA
Watts et al., (2000)	Experienced (RP 26 – 33)	Lead (25)	Pre-practised	177 (41)	148 (16)	162 (17)	NA	NA
Sheel et al., (2003)	Elite (>2 yrs competition)	TR Easy climbing (19)	Familiar	90 – 210	129 (13)	NR	45.3	NA
	Elite (>2 yrs competition)	TR Hard climbing (23)	Familiar	90 – 210	144 (14)	NR	51.2	NA
de Gues et al., (2007)	Expert (OS 25 – 27)	TR (27) at 120 – 135°	Pre-practised	189 (25)	168.7 (8)	175.1 (13.9)	88.2 (7.1)	NA
		TR (27) at 90°	Pre-practised	244 (38)	167.5 (9.5)	173.8 (8.8)	88 (9.4)	NA
		Traverse (27) 135-180°	Pre-practised	190 (68)	160.3 (8.8)	167.3 (9.9)	83.9 (7.5)	NA
		Traverse (27) 90°	Pre-practised	195 (51)	161.8 (8.4)	164.5 (10.5)	84.9 (7.6)	NA

Study	Ability definition (Ewbank)	Condition/route (Ewbank)	Route practise	Duration s ( $\pm$ SD)	Average HR bts·min <sup>-1</sup> ( $\pm$ SD)	HR <sub>peak</sub> bts·min <sup>-1</sup> ( $\pm$ SD)	% of bike/run/treadwall $\dot{V}$ O <sub>2max</sub> HR ( $\pm$ SD)	% of arm $\dot{V}$ O <sub>2max</sub> HR ( $\pm$ SD)
Bertuzzi et al., (2007)	Recreational (climb>23)	TR Easy (18) at 90°	Pre-practised	83.9 (20.1)	NR	171 (6)	NR	NA
	Elite (top 10 national ranking)	TR Easy (18) at 90°	Pre-practised	73.8 (17.6)	NR	162 (8)	NR	NA
	Elite (top 10 national ranking)	TR Moderate (22) at 120°	Pre-practised	80.8 (145.5)	NR	175 (5)	NR	NA
	Elite (top 10 national ranking)	TR Difficult (22) at 110°	Pre-practised	82.3 (16.4)	NR	181 (7)	NR	NA
Barnik & Jereb (2007)	23	Lead (14)	OS	NR	142 (19)	NR	NA	NA
		Lead (18)	OS	NR	155 (15)	NR	NA	NA
		Lead (21)	OS	NR	163 (15)	NR	NA	NA
Rodio et al., (2008)	Recreational male (16 – 23)	TR (14)	NR	NR	144 (16)	NR	83 (8)	NA
	Recreational female (16 – 23)		NR	NR	164 (13)	NR	90 (5)	NA
Draper et al., (2008)	Intermediate (14 – 15 traditional)	OS Lead (18)	OS	213 (46)	161 (6)	NR	NR	NA
		2 <sup>nd</sup> Lead (18)	2 <sup>nd</sup> Lead	199 (33)	159 (6)	NR	NR	NA
Draper et al., (2010)	Intermediate (Sport 19 – 22)	TR (19)	OS	87 (22)	NR	151 (20.8)	77	
		Sport lead (19)	OS	193 (30)	NR	159 (6)	81	NA
Romero et al., (2011)	Experienced (21 – 25)	TR week 1 (18)	Pre-practised	122 (36)	NR	157 (20.8)	NA	NA
		TR week 4 (18)	Pre-practised	116 (36)	NR	155.6 (19.4)	NA	NA
		TR week 6 (18)	Pre-practised	110 (24)	NR	156.6 (19.2)	NA	NA
		TR week 9 (18)	Pre-practised	98 (18)	NR	148.9 (16.7)	NA	NA
Bertuzzi et al., (2012)	Elite (>26)	TR (18)	OS	NR	NR	188 (6)	NA	NA
	Recreational (<23)	TR (18)	OS	NR	NR	183 (6)	NA	NA
Rosponi et al., (2012)	Skilled climbers (25 – 29 OS)	TR (19) Self selected pace(SS)	NR	~300	157 (15)	NR	NR	NA
		TR (19) 50% lower than self-selected pace	NR	~300	145 (21)	NR	NR	NA
		TR (19) 50% higher than self-selected pace	NR	~300	172 (11)	NR	NR	NA

TR = top rope, OS = on-sight, RP = red-point, NR = not reported, NA = not applicable

Like Watts and Drobish (1998) and Mermier et al. (1997), both de Geus et al. (2006) and Bertuzzi et al. (2007) investigated climbers ascending routes on different levels of steepness during vertical/upward climbing ( $90^\circ$  and  $120^\circ - 135^\circ$ ) and traversing ( $90^\circ$  and  $135^\circ - 180^\circ$ ) (de Geus et al., 2006); and on easy ( $90^\circ$ , 18 Ewbank), moderate ( $120^\circ$ , 22 Ewbank) and difficult ( $110^\circ$ , 25 Ewbank) routes (Bertuzzi et al., 2007). de Geus et al. (2006) studied expert climbers ( $n = 15$ ) with a best on-sight grade of 25 – 27 (Ewbank). Participants top roped four different routes of the same technical ability: a vertical climb at  $90^\circ$ , a traverse at  $90^\circ$ , a vertical/upward climb at  $120^\circ - 135^\circ$  and a traverse at  $135^\circ - 180^\circ$ . The authors reported very similar average  $\dot{V}O_2$  values across all angles with the lowest being during the traverse at  $90^\circ$  ( $32 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ), and the highest being on both vertical climbs ( $35.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ). Peak  $\dot{V}O_2$  values were notably higher than average values but remained similar across ascent styles with the biggest difference being seen in vertical climbing at  $90^\circ$  ( $8.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) and the smallest being in the traverse at  $135^\circ - 180^\circ$  ( $5.6 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ). As Billat et al. (1995), Watts and Drobish (1998) and Mermier et al. (1997) had reported minimal increases in  $\dot{V}O_2$  with increased climbing angle and difficulty (to  $151^\circ$  (Mermier et al., 1997)). de Geus et al. (2006), reinforced the theory suggested by Watts and Drobish (1998) that an arm-specific  $\dot{V}O_{2\text{max}}$  may have been attained as the upper body appears to be the primary contributor of work. A similar pattern was found for HR values. Average HR was higher than the corresponding  $\dot{V}O_2$  values, but were similar for vertical ascents ( $90^\circ = 167.5 \text{ bts}\cdot\text{min}^{-1}$ ,  $120 - 135^\circ = 168.7 \text{ bts}\cdot\text{min}^{-1}$ ) and these were marginally higher than both traverses ( $90^\circ = 161.8 \text{ bts}\cdot\text{min}^{-1}$ ,  $135 - 180^\circ = 160.3 \text{ bts}\cdot\text{min}^{-1}$ ). Peak HR values were only marginally higher than average values with the biggest difference being vertical climbing at  $120^\circ - 135^\circ$  ( $> 6.4 \text{ bts}\cdot\text{min}^{-1}$ ) and the smallest being  $90^\circ$  traverse ( $> 2.7 \text{ bts}\cdot\text{min}^{-1}$ ). When expressed as a percentage of maximal treadmill running, HR during all the climbing ascents represent similar values to Billat et al. (1995) who also compared values to treadmill exercise. However, de Geus et al. (2006) reported that the percentage of maximal treadmill  $\dot{V}O_2$  used throughout all of the four climbs was much higher compared to those reported by Billat et al. (1995). This may be due to the de Geus et al. (2006) participants having a higher on-sight grade (25 – 27 Ewbank). Billat et al. (1995) reported only that all participants in their study had at least three years experience, and so it is unclear what the actual ability level was.

During a later study examining the aerobic profiles of elite ( $n = 7$ ), intermediate ( $n = 7$ ) and non-climbers ( $n = 7$ ) during a maximal climbing specific arm crank test, Pires et al. (2011b) found that elite climbers could perform for significantly longer than intermediate climbers and non-climbers. Furthermore, at the first ventilatory threshold the power (W) was significantly higher in elites (Elite =  $69 \pm 9.4$ W and non-climbers =  $52.1 \pm 11.8$ W). Although ventilatory threshold was higher when expressed as W, the actual threshold expressed in  $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  was only marginally higher in the elite compared to all other groups. The authors concluded that elite indoor rock climbers elicited a higher level of aerobic fitness compared to a control group, and that there was no difference between the aerobic profiles of elite and intermediate indoor rock climbers.

**Table 3.6 Power, blood lactate, heart rate and oxygen consumption responses during maximal exercise tests, in all known major rock climbing studies (grades converted to Ewbank using Draper et al. (2011) Appendix G).**

Study	Ability Definition (Ewbank)	Test mode	$\dot{V}O_{2\max}$ mL·kg <sup>-1</sup> ·min <sup>-1</sup> (± SD)	HR <sub>max</sub> bts·min <sup>-1</sup> (± SD)	Average BLa Post mmol·L <sup>-1</sup> (± SD)	Anaerobic power W (± SD)
Billat et al., (1995)	High level (3 years experience)	Arm pulling max test	22.3 (2.6)	190 (9.7)	10.4 (4.5)	NR
		Treadmill $\dot{V}O_{2\max}$	54.8 (5)	205 (10.3)	10.9 (1.4)	NR
Watts & Drobish (1998)	Experienced	Treadmill	50.5 (7)	NR		NR
Booth et al., (1999)	Elite (OS 19 – 25)	Treadwall (max test)	43.8 (2.2)	190 (4)	10.2 (0.6)	NR
Mermier et al., (2000)	Male various (12 – 30)	Wingate bike lower body	NA	NA	NA	1230 (229) W
	Female various (12 – 30)	Wingate upper body ergometer	NA	NA	NA	494 (120) W
	Male various (12 – 30)	Wingate bike lower body	NA	NA	NA	728 (115) W
	Female various (12 – 30)	Wingate upper body ergometer	NA	NA	NA	289 (45) W
Sheel et al., (2003)	Elite (>2 yrs competition)	Cycle $\dot{V}O_{2\max}$	45.5 (6.6)	192 (11)	NR	259 (50) W
de Gues et al., (2006)	Expert (OS 25 – 27)	Treadmill $\dot{V}O_{2\max}$	52.2 (5.06)	192 (13)	10.27 (2.1)	NR
Bertuzzi et al., (2007)	Recreational (climb>23)	Upper body $\dot{V}O_{2\max}$	35.5 (5.2)	NR	NR	NR
	Elite (top 10 national ranking)	Upper body $\dot{V}O_{2\max}$	36.5 (6.2)	NR	NR	NR
	Elite (top 10 national ranking)	Wingate upper body	NR	NR	NR	1.9 (0.4) W·kg <sup>-1</sup>
	Elite (top 10 national ranking)	Wingate upper body	NR	NR	NR	2.1 (0.3) W·kg <sup>-1</sup>
Rodio et al., (2008)	Recreational male (16 – 23)	Cycle $\dot{V}O_{2\max}$	39.1 (4.3)	171 (8)	NR	NR
	Recreational female (16 – 23)	Cycle $\dot{V}O_{2\max}$	39.7 (5)	177 (4.5)	NR	NR
Romero et al., (2009)	Expert (22 – 30)	Treadwall (max test)	51.3 (4.5)	184.8 (7.68)	11.1 (3.2)	NR
	Elite (25 – 33)	Treadwall (max test)	51.9 (3.42)	189.8 (2.75)	10.5 (5.48)	NR
Pires et al., (2011)	Elite (climb>27)	Arm crank	36.8 (5.7)	184.3 (7.3)		130.9 (11.8) W
	Intermediate (>23)	Arm crank	35.5 (5.2)	175 (8.9)		122.1 (28.4) W
	Control	Arm crank	28.8 (5.0)	158 (22.1)		115.4 (15.1) W
Rosponi et al., (2012)	Skilled climbers (25 – 29 OS)	Cycle $\dot{V}O_{2\max}$	56.3 (4.9)	178.4 (6.1)		4.7 (0.31) W·kg <sup>-1</sup>

OS = on-sight, RP = red-point, NR = not reported, NA = not applicable



Draper et al. (2008) assessed intermediate climbers (14 – 16 (Ewbank) traditional (n = 10)) performing near or at their best performance grade. The authors compared the effects of an on-sight lead against a second lead ascent of the same route (17 Ewbank technical). The authors measured BLa,  $\dot{V}O_2$  and HR responses as well as pre-climb anxiety (CSAI-2R). Climb time was marginally longer during the on-sight lead compared to the second ascent (213 and 199s respectively). Average  $\dot{V}O_2$  for both lead and top rope ascents were low ( $26.54 \pm 2.46$  and  $25.98 \pm 2.48 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ), but were similar to previously reported average lead climb data (Billat et al., 1995; Watts et al., 2000). When  $\dot{V}O_2$  was reported as a percentage of maximal treadmill running, the percentages were also comparatively low (46 and 45%), although again, these are similar to Billat et al. (1995). It would appear that the percentage of treadmill  $\dot{V}O_{2\text{max}}$  used in rock climbing may differ between ability groups and the ascent styles. Although relative  $\dot{V}O_2$  during both the on-sight climbs and maximal treadmill running appear to be low in Draper et al. (2008), HR averages during both the on-sight lead ( $161 \pm 6 \text{ bts}\cdot\text{min}^{-1}$ ) and second lead ( $159 \pm 6 \text{ bts}\cdot\text{min}^{-1}$ ) are similar to almost all of the previous studies (Billat et al., 1995; de Geus et al., 2006; Mermier et al., 1997; Watts et al., 2000). Draper et al. (2008) reported that there were no significant differences in HR between an on-sight lead and second lead in intermediate climbers (n = 10). Yet there were significant differences between ascents for cognitive and somatic anxieties, suggesting that HR is not affected by an increase in anxiety during on-sight rock climbing in intermediate performers. Subsequently after this, Draper et al. (2010) reported no significant differences in cognitive and somatic anxieties for intermediate climbers (n = 9) on-sighting a route on top rope and lead. However, in this case there were significant differences in HR between ascent styles. At one minute post-lead climb HR was significantly elevated compared to the top rope ascent. The authors suggested that this increase in HR seen post one minute, was indicative of an increase in the fast component of excess post-exercise  $O_2$  consumption, and therefore a notable contribution of the ATP-PCr system may have been present.

Furthermore, when Bertuzzi et al. (2007) investigated the energy system contributions in sport climbing, the authors reported that the ATP-PCr system may potentially be more prevalent than first thought (Billat et al., 1995; Mermier et al., 1997). The previously mentioned differences in HR recovery between lead and top roped ascents reported by Draper et al. (2010) were not seen in the  $\dot{V}O_2$  response of the climbers. The

authors reported that the average  $\dot{V}O_2$  was only marginally higher in the lead (less than  $1 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) compared to the top rope ascent. The average and peak  $\dot{V}O_2$  values were low but similar to those reported by Draper et al. (2008) and Bertuzzi et al. (2007). The authors suggested that these were most likely due to methodological differences as both Billat et al. (1995) and Mermier et al. (1997) used Douglas bags instead of online gas analysis systems. Furthermore, these results suggest that the relative aerobic contributions to both lead and top roped performances may have been similar, despite large differences in climb time (top rope =  $87 \pm 22\text{s}$  and lead =  $193 \pm 30\text{s}$ ).

More recently, it has been suggested that both pre-practising a route and the pace with which it is ascended may have a profound effect on the HR and  $\dot{V}O_2$  response in climbers. España-Romero et al. (2012) studied the physiological responses of repeated ascents on experienced (21 – 25 Ewbank) rock climbers over a ten-week period (one ascent per week). Climbers were asked to ascend the route once per week for the entire ten week period. The authors reported that climbing time was significantly longer for ascent/week one ( $122 \pm 36\text{s}$ ) compared with ascents four, six and nine. Although not significantly different, it was reported that peak HR decreased in week nine ( $148.9 \pm 16.7 \text{ bts}\cdot\text{min}^{-1}$ ) compared to weeks one, four and six ( $157 \pm 20.7$ ,  $155.6 \pm 19.4$  and  $156.6 \pm 19.2 \text{ bts}\cdot\text{min}^{-1}$  respectively). Furthermore, there were no significant differences between peak  $\dot{V}O_2$  values during any of the ascents (all differences were less than  $1 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ). However, it should be noted that the climbers ascending the route were performing below their best self-reported ability grade and so an efficient technique may have been used from the start (during the first ascent). Experienced and skilled climbers have been suggested to see the most efficient ways to ascend a route just by looking at it and mentally working the moves before the first attempt (Horst, 2008). This is especially notable in competition climbers who ascend on-sight on a regular basis as part of their training schedules (Priestley, 2010).

### **3.8.2 Energy expenditure**

A summary of journal articles that have published data regarding EE in rock climbing can be found in Table 3.4. As there was very little published research into what was at the time a rapidly growing sport in Europe and the USA, Mermier et al. (1997) aimed to

provide a greater understanding of some of the many unknown physiological responses during indoor climbing. One aim of their study was to quantify the EE during three increasingly difficult top roped (easy 12, moderate 16 and difficult 21 (Ewbank)) climbs in experienced male and female climbers ( $n = 14$ ). It was hypothesised that there would be significant differences in EE between the three different climbs due to the graded nature of the routes. They found marginal increases in EE with increasing difficulty, yet the only significant difference was seen between easy and difficult climbing (12 and 21 Ewbank). Energy expenditure was at the rate of 0.149, 0.159 and 0.202 kcal·kg<sup>-1</sup>·min<sup>-1</sup> for easy, moderate and difficult climbing respectively. Since the authors had reported marginal increases in  $\dot{V}O_2$  and HR (reported in section 3.8.1) with the increasing difficulty of climbing, it was not surprising that there were corresponding increases in EE. An interesting observation was that as climbing distance decreased with an increasing wall angle, the EE per metre climbed significantly increased at 96° (2 kcal·m) and 102° (5 kcal·m) (for a projected weight of a 70kg person). The authors also suggested that the steeper angles appeared to cause a reduction in mechanical efficiency, and it was at this point that BLa began to significantly increase past (91°).

Watts and Drobish (1998) reported similar findings in their study, there was little difference in absolute kcal (10.4 – 11.2 kcal·min<sup>-1</sup>) between the five climbing angles (80°, 88°, 91°, 98°, 102°), and this was mimicked by the small increases in  $\dot{V}O_2$ . However, similar to Mermier et al. (1997), when broken down into ascent angle and then distance, Watts and Drobish (1998) also reported that kcal significantly increased at angles beyond almost vertical (91°+). It should be noted that these values do not represent actual indoor or outdoor rock climbing as Watts and Drobish (1998) performed these tests using a treadwall. Although the mechanics of the motions remain similar on a treadwall, many aspects change such as decision making, climb time, route planning, rest periods, changes in climbing speeds and moving through crux sections of a route.

Whilst investigating energy system contributions and training status, Bertuzzi et al. (2007) reported absolute values of EE during top rope climbing on an indoor wall in both recreational ( $n = 7$ ) and elite performers (top 10 ranking climbers in National Championships,  $n = 6$ ). As previously mentioned the climbers ascended easy (18 Ewbank at 90°), moderate (21 Ewbank at 120°) and difficult (25 Ewbank at 110°)

routes. Unlike the previous studies reporting values of EE, Bertuzzi et al. (2007) did not always increase the climbing angle to increase difficulty. The hardest route was at 100°, compared to the easier climbs at 90° and 120°. Therefore, the hardest route must have had a greater technical difficulty (i.e. fewer and smaller holds). During easy climbing elite performers had a lower average  $\dot{V}O_2$  than their recreational counterparts and this was matched with a lower EE (elite = 17.05 kcal and recreational = 97.1 kcal). Energy expenditure in the elite performers increased as climbing difficulty increased. Unlike previous studies (Mermier et al., 1997; Watts & Drobish, 1998) this increase in EE was not caused by purely an increase in climbing angle, it also took into consideration an increase in the technical difficulty of the route (size, shape and frequency of holds). Furthermore, climb time was similar across all difficulties and angles ascended by the elite performers (total variance was ~ 9s). This suggests that EE may not solely be affected by ascent angle and distance climbed, but also by the technical difficulty involved in the route (size, shape and frequency of holds).

More recently Rosponi et al. (2012) assessed the effect of speed of ascent on rock climbing economy. As previously mentioned (section 3.8.1), the authors had skilled climbers (best on-sight 25 – 29 Ewbank) ascend routes at different speeds. They reported that with higher climbing speeds EE was significantly reduced when climbing for a similar duration (~ 300s). When climbing at 50% below a self-selected climbing speed, at a self-selected speed and then 50% above the self-selected speed, relative EE increased,  $21.57 \pm 1.12$ ,  $16.79 \pm 1.12$  and  $13.25 \pm 3.15$  kcal·min<sup>-1</sup> (respectively). The results show that EE is in part dictated by the speed of ascent and not purely climbing angle, distance climbed and technical difficulty.

Energy expenditure has been investigated for speed of ascent, ascent angle, distance climbed and technical difficulty of the climb. During an investigation into the physiological responses of repeated ascents in rock climbing, España-Romero et al. (2012) reported that absolute EE changes over time with repeated ascents. The authors suggested that EE during a climb appears to decrease as the number of ascents increased (one ascent was completed per week); reported values were  $17 \pm 5.1$  kcal in ascent one (week one) compared to  $11.5 \pm 3.2$  kcal during ascent nine (week nine). As climb time also decreased, these findings appear to agree with the later work of Rosponi et al. (2012), that increasing the speed of an ascent, decreases the EE. Interestingly, this pattern was not mimicked throughout the ten minute post-recovery period, in fact EE

increased from ascent one to four before beginning a slow decline to ascent nine. It was suggested that during the interval between ascents one and four, the faster rate of climbing may have produced metabolic and physiologic consequences that resulted in EE increasing during the recovery period.

### **3.8.3 Blood lactate responses**

A summary of studies that have measured BLa concentrations both pre and post-climbing trials are presented within Table 3.7. It is clear that BLa concentration increases with bouts of rock climbing. However, concentrations do not reach those that have been reported in other sports such as running, cycling and rowing (Baker, Thomas, Cooper, Davies, & Robergs, 2012; Giles et al., 2006) unless a treadwall is used during a climbing specific maximal test to exhaustion (Booth et al., 1999). When a treadwall is used, BLa has been seen to rise from resting values ( $\sim 1 \text{ mmol}\cdot\text{L}^{-1}$ ) to  $10.2 \pm 0.6 \text{ mmol}\cdot\text{L}^{-1}$  (Booth et al., 1999). Although climbing is a whole body activity, the predominant work stems from the upper body, specifically the forearms (Giles et al., 2006; Pires et al., 2011a; Sheel, 2004; Watts, 2004). These small muscle groups do not have the same metabolic potential as larger groups which are used during whole body dynamic exercises such as running and cycling, and therefore BLa concentrations are notably lower (Giles et al., 2006).

Table 3.7 suggests the concentrations of BLa appear to vary depending on the climbing protocol used. Blood lactate concentrations have been reported as low as  $1.6 \text{ mmol}\cdot\text{L}^{-1}$  (Mermier et al., 1997) and as high as  $7.77 \text{ mmol}\cdot\text{L}^{-1}$  (Bertuzzi et al., 2012) during rock climbing ascents (excluding maximal treadwall tests). These large variations in BLa concentrations are probably due to the range of climbing methods used, the different styles of climbing and the large spread of participants' ability levels. It is clear from the values reported within Table 3.7 that with increasing climbing difficulty, whether due to the technical grade or angle of ascent, there is an increase in BLa concentration post-climbing. Numerous studies have shown that when difficulty increases during treadwall climbing (Watts & Drobish, 1998), indoor top roping (Bertuzzi et al., 2007), an on-sight lead ascent compared to a second ascent (Draper et al., 2008), on-sight top roping compared to lead climbing (Draper et al., 2010) and increasing the speed of ascent (Rosponi et al., 2012), post-BLa concentrations are increased. These increases with

specific difficulties have been attributed to numerous causes, the most prevalent being the greater the working demand placed on the small muscle groups and a greater anaerobic contribution. Furthermore, the more overhung a climb is, the greater the force placed on the forearms during the ascent which consequently increases the working load for the muscle group.

Increases in BLa have been significantly correlated with decreases in handgrip strength ( $p < 0.05$ ,  $R = 0.76$ ), but interestingly not with decreases in hand grip endurance ( $p > 0.05$ ,  $R = 0.56$ ) (Watts et al., 1996). However, as previously mentioned (section 3.6.1) this was using HGD which was later shown to be non climbing specific and furthermore, a poor predictor of performance (Watts et al., 2008). To date no known studies have explained the potential relationships between BLa and a climbing specific measure of handgrip performance. Also concerned with the performance aspects of BLa, Werner and Gebert (2000) measured BLa concentrations of 46 competitors ( $n = 28$  male, 18 female) during a World Cup climbing event. Blood lactate concentrations were  $6.7 \pm 1.1 \text{ mmol}\cdot\text{L}^{-1}$  for ascents with an average height of  $13.2 \pm 4.9\text{m}$ . The authors reported that BLa was significantly correlated to the height gained during the competition ( $R = 0.41$ ,  $p < 0.05$ ).

**Table 3.7 Blood lactate responses during all known major rock climbing studies  
(Grades converted to Ewbank using Draper et al. (2011) Appendix G).**

Study	Ability Definition (Ewbank)	Condition (Ewbank)	Route practise	Duration s ± (SD)	Average BLa Post mmol·L <sup>-1</sup> ± (SD)
Billat et al., (1995)	High level (3 years experience)	Lead (25)	5 hours on route	176 (140)	4.3 (0.77)
		Lead (25 considered harder)		159 (14.7)	5.75 (0.95)
Mermier et al., (1997)	Experienced (Not reported)	TR (12) at 90°	NR	300	1.6
		TR (16) at 106°	NR	300	2.4
		TR (21) at 151°	NR	300	3.2
Watts & Drobish (1998)	Experienced (basic course)	Treadwall (14) at 80°	Familiarisation climb	240	3.6 (1.2)
		88°		240	4 (1.3)
		91°		240	4.9 (1.6)
		96°		240	5.1 (1.3)
		102°		240	5.9 (1.2)
Booth et al., (1999)	Elite (OS 17 – 25)	Treadwall	Familiarisation	446.4	10.2 (0.6)
Watts et al., (2000)	Experienced (RP 26 -33)	Outdoor (18) lead	Pre-practised	441.6	4.51 (0.5)
		Lead (25)	Pre-practised	177 (41)	Post-1 min 5.7 (1.7)
		Active recovery			
		Lead (25)	Pre-practised	177 (41)	Post-1 min 6.8 (1.9)
de Gues et al., (2006)	Expert (OS 25 – 27)	Passive recovery			
		TR (27) at 120 – 135°	Pre-practised	189 (25)	6.19 (1.61)
		TR (27) at 90°	Pre-practised	244 (38)	5.95 (1.8)
		Traverse (27) at 135 – 180°	Pre-practised	190 (68)	5.55 (1.66)
		Traverse (27) at 90°	Pre-practised	195 (51)	4.84 (1.3)
Bertuzzi et al., (2007)	Recreational (climb>23) Elite (top 10 national ranking) Elite (top 10 national ranking) Elite (top 10 national ranking)	TR Easy (18) at 90°	Pre-practised	83.9 (20.1)	4.4 (1.6)
		TR Easy (18) at 90°	Pre-practised	73.8 (17.6)	2.4 (0.9)
		TR Moderate (22) at 120°	Pre-practised	80.8 (145.5)	3.7 (0.8)
		TR Difficult (25) at 110°	Pre-practised	82.3 (16.4)	3.9 (1.8)
Rodio et al., (2008)	Recreational male (5a – 7a)	TR (14)	NR	NR	1.6 (0.3)
	Recreational female (5a-7a)		NR	NR	3.3 (1.6)
Draper et al., (2008)	Intermediate 14 – 15 (traditional)	OS sport lead (18)	OS	199 (33)	3.7
		2 <sup>nd</sup> Lead (18)	2 <sup>nd</sup> Lead	87 (22)	3
Heyman et al., (2009)	Well trained (>3 years experience)	Passive recovery 1	Pre-practised	573 (307)	Δ of post – pre 4.66 (2.15)
		Active recovery 1	Pre-practised	471 (199)	Δ of post – pre 4.74 (0.97)
		Electromyostimulation 1	Pre-practised	562 (358)	Δ of post – pre 5.15 (1.9)
		Cold water emersion 1	Pre-practised	551 (312)	Δ of post – pre 4.05 (1.65)
		Passive recovery 2	Pre-practised	415 (180)	Δ of post – pre 2.92 (1.54)
		Active recovery 2	Pre-practised	455 (173)	Δ of post – pre 4.26 (1.28)
		Electromyostimulation 2	Pre-practised	445 (221)	Δ of post – pre 2.7 (1.36)
		Cold water emersion 2	Pre-practised	549 (250)	Δ of post – pre 3.3 (1.6)
Draper et al., (2010)	Intermediate (sport 19-22)	TR (19)	OS	87 (22)	2.5 (0.9)
		Lead (19)	OS	193 (30)	3.1 (0.6)
Bertuzzi et al., (2012)	Elite (>26)	TR (18)	OS	NR	Peak 7.77 (1.07)
	Recreational (<23)	TR (18)	OS	NR	Peak 7.42 (2.12)
Rosponi et al., (2012)	Skilled climbers (25 – 29 OS)	TR (19) Self selected pace (SS)	NR	~300	Δ of 4min post - pre 1.91 (1.1)
		TR (19) 50% lower than self selected pace	NR	~300	Δ of 4min post - pre 1.5 (1.7)
		TR (19) 50% higher than self selected pace	NR	~300	Δ of 4min post - pre 4.9 (1.9)

TR = top rope, OS = on-sight, RP = red-point, NR = not reported, NA = not applicable

Blood lactate recovery has been of great interest to researchers due to its practical application to performance. It has been suggested that for concentrations of BLa to return to normal pre-climb values it can take up to 30 minutes (Watts et al., 2000). Several studies have sought to investigate the effects of different recovery methods on both rock climbing (Heyman, de Geus, Mertens, & Meeusen, 2009; Watts et al., 2000) and bouldering (Draper, Bird, Coleman, & Hodgson, 2006a). Watts et al. (2000) assessed  $\dot{V}O_2$  consumption, HR and BLa throughout a difficult climb (on lead, grade 25 Ewbank) in participants ( $n = 15$ ) who had a best red-point grade of 26 – 33 (Ewbank). Climbers were asked to partake in either active ( $n = 8$ ) or passive ( $n = 7$ ) recovery. Active recovery consisted of recumbent cycle-ergometry at 25W and BLa was measured at one minute post-climb, and then every 10 minutes post-climb for a 30 minute period. Blood lactate in the active recovery group had returned to the pre-climb concentrations by 20 minutes post-climb. In the passive recovery group, BLa returned to the pre-climb concentrations (these were elevated due to a warm-up and stretching) after 30 minutes post-climb. Handgrip strength (measured by a HGD) did not return to pre-values within the 30 minute rest period for either the active or passive recovery group.

Draper et al. (2006a) reported similar findings to those of Watts et al. (2000). Draper et al. (2006a) studied the effects of short duration active recovery (walking) on five successive bouldering performances ( $n = 10$ ). The authors reported that both BLa and Rate of Perceived Exertion (RPE) (developed by Borg (1982)) were significantly lower across all five bouldering trials for the active recovery protocol. Furthermore, climbers in the active group began each ascent with lower BLa levels than those seen during the passive protocol, and participants indicated lower RPE scores at the end of each trial.

de Geus, Nicolas, Inge, and Romain (2007) studied the effects of three different recovery strategies (active, passive and electro-stimulation) after a competition style route. Climbers ascended an increasingly difficult route until failure. Participants were subsequently given either a passive, active (cycling at 40W) or electro-stimulation recovery protocol for a 20 minute period before making a second ascent on the same route. During the second ascent, the climbers in the active and electro-stimulation group had managed to climb for significantly longer, completed more moves and had subsequently attained higher concentrations of BLa compared to the passive recovery group.



In more main stream sports, such as cycling and running, the sampling of BLa and other metabolites has generally been conducted from one of the distal ends of a fingertip (Garland & Atkinson, 2008). When a runner or cyclist is asked to perform repeated sprints, taking samples from a fingertip does not in any way impede the athlete's performance. However, in rock climbing taking a capillary sample from the fingertip, particularly pre-climb, can be extremely problematic for repeated ascents and could affect the performer both physically and psychologically (Draper, Brent, Hale, & Coleman, 2006b). Despite this somewhat obvious methodological problem, numerous rock climbing studies have sampled capillary blood from fingertips (Booth et al., 1999; Draper et al., 2010; Watts & Drobish, 1998). Draper et al. (2006b) attempted to resolve this problem by sampling BLa from the earlobe, in a study which also compared lactate analyzers (YSI and Lactate Pro). The results showed that for BLa concentrations measured pre, post and five minutes post-climb, all data points fell within the upper and lower bounds of the 95% confidence interval (CI) (with the exception of one data point in pre-climb). However, mean BLa concentrations were consistently lower in the ear lobe compared to the fingertip for both the Lactate Pro and the YSI analyzers. The use of regression modelling provided clear adjustments for both post ( $R^2 = 0.930$ ,  $y = 0.953x + 0.672$ ) and five minute post-climb ( $R^2 = 0.930$ ,  $y = 0.956x + 0.460$ ) samples when using a portable Lactate Pro instrument. Although sampling from the earlobe appeared to be reliable, it poses problems with repeated samples; the earlobe does not sample well and often needs to be squeezed very firmly, putting the samples at risk of being lysed and consequently artificially altering the BLa concentration. Minimally invasive and sport specific sampling methods which assess BLa concentrations and other blood based metabolites are yet to be found for repeated rock climbing ascents, particularly when multiple samples are required for the assessment of other metabolites found in the blood, such as cortisol.

### **3.8.4 *Energy system contribution***

The route and style by which a climb is ascended depends on a number of variables, including anthropometric make-up of the climber and their psychological approach to the task. Consequently, this makes defining the energy system contribution within the sport very difficult. There is limited data in this area. Billat et al. (1995) was the first author to attempt to define the extent to which the oxidative metabolism is used within

competitive rock climbing. The main focus of the study was identifying the percentage of maximal (treadmill running)  $\dot{V}O_2$  used throughout the ascent in relation to the ascent time. As only a small fraction of the  $\dot{V}O_{2\max}$  was used, the authors deemed that the aerobic contribution was minimal despite the average climb time being more than 3 minutes 30s. It was deemed that the lengthy ascent time was due to the observed static time being 37%. However, the authors did suggest that during steeper sections, the aerobic contribution may be greater.

Later, and contradicting the works of Billat et al. (1995), Sheel (2003) suggested that with increasingly difficult climbs, there was an increased reliance on the aerobic system. The authors reported that when comparing maximal cycle ergometry to climbing an 'easier' (maximum minus three full grades) and 'harder' (max ability minus two full grades) route, the fraction of  $\dot{V}O_{2\max}$  used was significantly higher during "harder" climb. Yet in a study of elite and recreational climbers, Bertuzzi et al. (2007) suggested that the aerobic and anaerobic alactic systems were the predominant energy systems during indoor climbing, but the training status, route difficulty and upper body power may not directly influence the contribution of the energy systems used throughout the ascents. However, it should be noted that this latter study used small sample sizes in both the recreational ( $n = 6$ ) and elite ( $n = 7$ ) groups. The authors noted that the increased aerobic contribution probably occurred to meet the energy demand imposed by taking rests on the route to shake out and chalk up the hands. This in turn would have aided in the partial re-synthesis of the high energy phosphate stores in the muscle.

As previously mentioned, it has been suggested that more advanced climbers will spend a greater amount of time inspecting a route before making an ascent to maximise on-route efficiency (Goddard & Neumann, 1994). Furthermore, in kinematic studies of rock climbers, it has been shown that the more experienced a climber is, the smaller the contact force, the shorter the contact time, the smaller the impulse, the better the smoothness factor and the higher the coefficient of friction (Fuss & Niegl, 2008). These factors suggest that more advanced rock climbers will tend not to over recruit on holds. This in turn could potentially mean that the forearm flexors such as the digitorum profundus may not be as isometrically contracted and thus cause a reduced build up of metabolites, and an increase in the rate of re-synthesis of high energy phosphates within the flexor itself.

It appears that the fraction of treadmill  $\dot{V}O_{2\max}$  used throughout a climb varies considerably, depending on the style of ascent and profile of the climb. Values have been reported as low as 42% during an on-sight top rope climb in intermediate climbers (Draper et al., 2010), and as high as 69.6% during a top roped ascent by expert climbers ascending at 120 – 135° (de Geus et al., 2006). Data within Table 3.4 suggests that climbing on steeper wall angles (more over-hung routes) appears to require a greater portion of  $\dot{V}O_{2\max}$ . Furthermore, there is some evidence to suggest that climbers with a greater level of ability may be able to activate a larger amount of aerobic contribution during difficult ascents (Billat et al., 1995; Sheel, 2004), yet to what extent remains unclear.

Relative to other more whole body and dynamic sports, maximal or near maximal climbing appears to use a relatively low fraction of treadmill  $\dot{V}O_{2\max}$ . However, there does appear to be a climbing  $\dot{V}O_2$  plateau, or  $\dot{V}O_2$  steady-state which is reached during an ascent (Giles et al., 2006; Watts & Drobish, 1998). As previously mentioned (section 3.8.1), it has been reported that this plateau in the  $\dot{V}O_2$  could be related to the possibility of an arm specific  $\dot{V}O_{2\max}$  being attained (Giles et al., 2006; Watts et al., 2000; Watts & Drobish, 1998). It could be that the arms reach a point at which maximal oxidation is able to be sustained for a period of time, as other limbs have been shown to receive and use the excess BLa from exercising muscles (Hermansen & Stensvold, 2008). The high HR and increased blood pressure seen in rock climbing could be an indication of an increased presser response. This may in part explain how climbers can continue to ascend for a short period when  $\dot{V}O_2$  appears to be at a maximum. Interestingly, when climbing  $\dot{V}O_2$  was compared against maximal arm crank  $\dot{V}O_2$ , the percentage of maximum exceeded the values seen in the arm crank in all elite climbers ascending easy, moderate and difficult routes on top rope (Bertuzzi et al., 2007).

More recently, elite climbers have been shown to be able to elicit higher  $\dot{V}O_{2\max}$  values during arm crank exercises than intermediate and non-climbers (Pires et al., 2011a). The elite values from Pires et al. (2011a) ( $36.8 \pm 5.7 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ) and Bertuzzi et al. (2007) ( $36.5 \pm 6.2 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ) were similar to  $\dot{V}O_{2\max}$  values reported during cycle ergometry, by Rodio et al. (2008) and Sheel (2003) ( $39.1 \pm 4.3 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  and  $45.5 \pm 6.6 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  respectively). Therefore, although climbers appear to use a

relatively low fraction of treadmill  $\dot{V}O_{2\max}$ , the  $\dot{V}O_2$  values reported for elite climbers during maximal arm crank and difficult climbing ascents appears to be larger than climbers of a lesser ability, and  $\dot{V}O_2$  utilisation maybe more specific to the upper body than previously first thought. It could be that the extensive climbing training seen in elite performers may cause an arm specific  $\dot{V}O_{2\max}$  which requires a greater level of aerobic contribution than previously believed.

Many problems arise when assessing energy system contributions during rock climbing. Not only are there issues in the style, route profile, manner and approach to climbing, but there are numerous technical difficulties which are yet to be tackled within the field. The use of breath-by-breath analysis in climbing studies within the last one and a half decades has helped to gain a better understanding of the  $\dot{V}O_2$  kinetics throughout different climbs with regards to whole body  $\dot{V}O_2$ . However,  $O_2$  uptake measured at the mouth has been generally used for characterizing pulmonary  $O_2$  kinetics during transitions in climbing such as during the onset of a climb or during recovery, as presented by Bertuzzi et al. (2007). Pulmonary  $O_2$  kinetics represents the culmination of muscle  $\dot{V}O_2$  and  $\dot{V}O_2$  from the rest of the body as well as connective  $O_2$  transport and changes in lung gas stores (Behnke, Barstow, & Poole, 2005). This can pose many problems for upper body  $\dot{V}O_2$  assessments. It was shown from an early stage that there was a delay or lag evident in leg  $\dot{V}O_2$  at the onset of contractions (Grassi et al., 1996). Although more recently an understanding of the kinetics of individual muscles has been possible (Behnke et al., 2002), the mitochondrial matrix had to be directly studied first. This means that conclusions regarding specific muscle  $\dot{V}O_2$  responses, such as for the forearm flexors during a climb or on an arm specific  $\dot{V}O_{2\max}$  test, must be made with extreme caution. It should be noted that advances in the technical measures associated with measuring pulmonary ventilation and its potential reflection of muscle  $\dot{V}O_2$  (particularly phase II pulmonary kinetics), and consequently muscle energetic, have been conducted under strict conditions in healthy humans (Rossiter et al., 2004a, 2004b). However, these techniques have yet to be used within a rock climbing context.

### 3.8.5 *Biochemical responses*

With the exception of one early study by Williams et al. (1978), investigations into hormonal responses during rock climbing have only been reported within the last six years. These investigations can be grouped into two main types; those that have focused on oxidative stress (Cesur et al., 2012; Magalhães et al., 2007; Merrells, Friel, Knaus, & Suh, 2008a; Sherk et al., 2011), and those that have attempted to understand the psychophysiological response to climbing (Hodgson et al., 2009; Williams et al., 1978).

Previous research has suggested there may be an increased  $\dot{V}O_2$  and subsequent reliance on the aerobic metabolism during rock climbing, particularly on difficult or over-hung climbs (Billat et al., 1995; Sheel, 2004). In rock climbing studies, a mass action effect initiated by an increase in the  $\dot{V}O_2$  response has been suggested to generate abnormally high concentrations of reactive oxygen nitrogen species (RONS) (Fridovich, 2008). Furthermore, isometric contraction, (similar to that seen in rock climbers) has been shown to increase RONS production, mediated by ischemia-reperfusion and purine catabolism-related increases in xanthine oxidase activity (Packer & Hiinnincn, 2000), acidosis (Siesjö, Bendek, Koide, Westerberg, & Wieloch, 1985) and catecholamine autooxidation (Cohen & Heikkila, 1974). Magalhães et al. (2007) suggested that it was because of these reasons that indoor rock climbing could potentially exacerbate cellular oxidative stress (an imbalance between enhanced RONS production and the ability of the antioxidant systems to render them inactive and cause cellular loss of redox homeostasis, as well as oxidative damage to cellular lipids, proteins and DNA). The authors focused on a competition style of climbing, and all participants ( $n = 14$ ) ascended until they had a fatigue-induced fall. Climbers were later asked to conduct a treadmill test where they ran for the same period of time as their climbing trial at a velocity which matched their average  $\dot{V}O_2$  consumption. The authors found that indoor climbing to fatigue induced plasma-oxidative stress. It was proposed that the nature of this stress was due to an  $O_2$  mass action effect and mediated RONS production, most probably from the ischemia-reperfusion related to the sustained and intermittent contractions of the forearm flexors (Magalhães et al., 2007).

More recently, Cesur et al. (2012) suggested that when an eight week climbing program is implemented for sedentary individuals, there was a decrease in total antioxidant status and an increase in total oxidant status. Furthermore, over the 24 hours after the climbing

session, there was an additional increase in free radical production and an overwhelming increase in the antioxidant capacity. The authors suggest that their findings further add to the belief that there may be a substantial contribution from the aerobic metabolism in climbing. They also go on to suggest that due to the changes in total antioxidant and oxidant status, indoor rock climbing increases plasma oxidative stress in sedentary individuals.

Sherk et al. (2011) studied the hormone responses of a prolonged bout of rock climbing on a treadwall. They were interested in whether or not a climbing based workout had an acute effect on testosterone, growth hormone and cortisol. Both testosterone and growth hormone are important mediators of lean tissue synthesis, and cortisol has been suggested to promote the breakdown of protein (Beaven et al., 2008; Goodman, 2009). These hormones have all been reported to increase during bouts of resistance training as well as during aerobic exercise in healthy individuals (Craig, Brown, & Everhart, 1989; Kindermann et al., 1982). Sherk et al. (2011) found that immediately after a climbing based work out, which lasted up to 30 minutes, both testosterone and growth hormone significantly increased whilst the cortisol concentrations remained unchanged. Furthermore, growth hormone remained significantly elevated fifteen minutes post-exercise, whereas testosterone levels had almost returned to values seen pre-climb. However, it should be noted that elevated cortisol responses are often seen fifteen to 30 minutes post-exercise (Levine, Zagoory-Sharon, Feldman, Lewis, & Weller, 2007), and therefore the authors may have not have captured the highest cortisol concentration. Sherk et al. (2011) suggested that the increases seen in testosterone concentration were similar to those previously reported after a 90-minute resistance work out (Jensen et al., 1991), but smaller than these seen during 30 minutes of running (Webb, Wallace, Hamill, Hodgson, & Mashaly, 1984). The findings suggest that in young male rock climbers, this form of training may be effective for eliciting an anabolic hormone response. Due to the biochemical pathways and responses to differing stresses to cortisol, growth hormone and testosterone, these findings cannot be applied to the general population of climbers and more work is required to investigate changes within a wider range of abilities and ages, as well as exploring potential gender related differences.

### **3.9 Summary**

The earliest significant body of rock climbing research began with A&E departments quantifying rates of accidents and injuries in specific geographical locations around the world. However, as the sport increased in popularity and competitiveness worldwide, a greater number of injuries to the extremities were reported. Surgeons investigated new treatments for these injuries and basic training programs were recommended as forms of prevention. As competition rock climbing became internationally competitive in the early 1990's the ICC and the IFCS were formed to adjudicate and raise the sports competitive profile. Scientists began to attempt to define the anthropometric makeup of elite level climbers. Unfortunately, there were many methodological inadequacies within these early studies, including the use of HGD instead of a sport specific measure of strength. Research over the last 20 years has placed a notable focus on trying to understand the physiological responses of rock climbing in many of its disciplines. However, many physiological aspects of sport rock climbing are yet to be determined, including the extent of anaerobic-aerobic contribution during a sport climb. Much of the confusion has been due the level of perceived risk associated with the sport and the potential influence of the nervous response on the physiological mechanisms during an ascent. The following chapter 'Introduction to Study One' will describe in detail the current but limited psychological and psychophysiological research in rock climbing. Furthermore, the chapter will highlight the omitted areas of research, which if conducted would help to ascertain the psychological component of on-sight rock climbing and its potential effect on the physiological responses.

## **Introduction to Study One**

### **4.1 Psychological research in climbing**

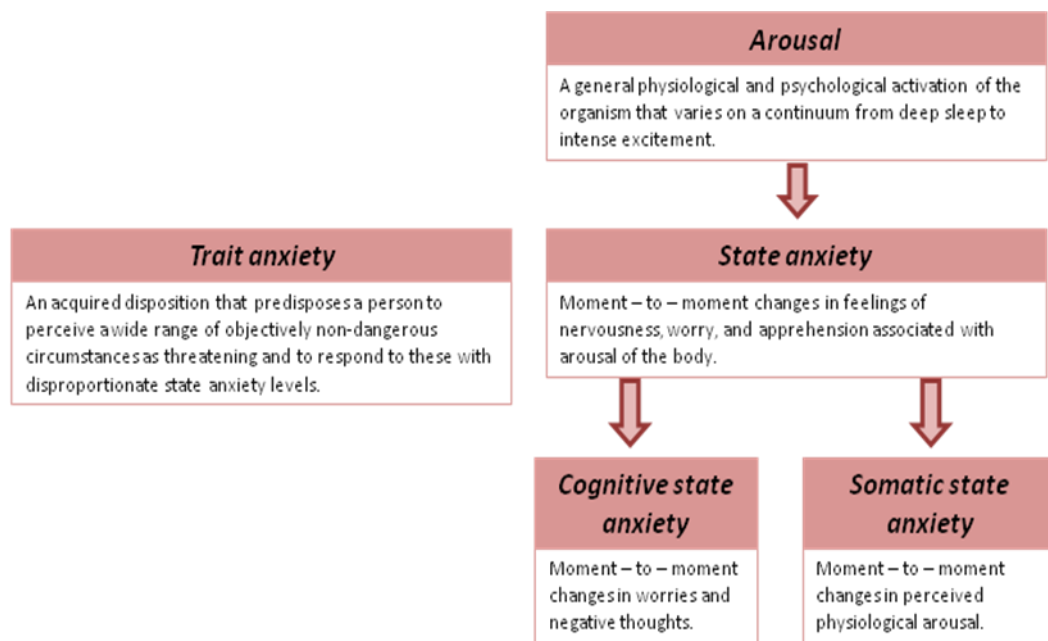
Rock climbing was generally conducted as a means of exploration throughout the 19<sup>th</sup> Century. During the early part of the 20<sup>th</sup> Century climbing became a leisure activity for many people. However, it wasn't until the 1970's that it became a competitive sport in its own right. This may in part explain why there has been little published research investigating the psychology of rock climbing until recent years. Despite the extensive research into anxiety within mainstream sports, to date there have been five known published research articles focusing purely on this aspect of sport performance (Aşçi, Demirhan, Koca, & Dinç, 2006; Feher, Meyers, & Skelly, 1998; Hardy & Hutchinson, 2007; Maynard, MacDonald, & Warwick-Evans, 1997; Robinson, 1985). Other studies in the area of psychology have focused on the effects of performance cues (Sanchez, Boschker, & Llewellyn, 2010a), and efficacy of a pre-ascent climbing route visual inspection (Sanchez, Lambert, Jones, & Llewellyn, 2010b). Considering the potential for increased psychological stress within the sport, and the discipline 'sport climbing' being acknowledged by the IOC, it is surprising that such little research currently exists.

Those climbing studies that have investigated anxiety within rock climbers have predominantly done so using the Competitive State Anxiety Inventory 2-Revised (CSAI-2R) developed by Martens, Vealey, and Burton (1990). This instrument contains three nine-item subscales: cognitive anxiety, somatic anxiety and self-confidence. Cognitive anxiety reflects the mental component of the anxiety response, caused by negative expectations about success, or negative self-evaluation. Somatic anxiety reflects evaluation of the physiological component of anxiety, such as an increase in HR or sweaty palms.

In addition to cognitive and somatic anxieties, it is important to distinguish between state and trait anxiety. Weinberg and Gould (2010) suggested that state anxiety is an emotional state "characterized by subjective, consciously perceived feelings of apprehension and tension, accompanied by or associated with activation or arousal of the autonomic system" (pg 79). Therefore, cognitive state anxiety refers to the extent that one worries or has negative thoughts, whereas somatic state anxiety refers to



moment-to-moment changes in perceived physiological activation (Weinberg & Gould, 2006). Trait anxiety is imbedded within personality, an acquired behaviour. Weinberg and Gould (2010) suggested that trait anxiety “predisposes an individual to perceive as threatening, a wide range of circumstances that objectively are not actually dangerous physically or psychosocially. The person then responds to these circumstances with state anxiety reactions or levels that are disproportionate in intensity and magnitude to the objective danger” (pg 79). The interrelationships between arousal, cognitive, somatic, trait and state anxiety are displayed in Figure 4.1.



**Figure 4.1 Interrelationships among arousal, state anxiety as well as cognitive and somatic anxieties (Weinberg & Gould, 2006).**

Based on these concepts, rock climbing studies have investigated: the changes in cognitive and somatic anxieties as well as self-confidence in novice rock climbers (Maynard et al., 1997), group changes in the state and trait attributes of moderate and advanced rock climbers (Feher et al., 1998), quantified pre-competitive anxiety as well as affective states (Aşçi et al., 2006), quantified the effect of performance anxiety on effort and performance in rock climbers (Hardy & Hutchinson, 2007) and assessed the relationships pre-performance psychological states has on performance in an elite climbing competition (Sanchez et al., 2010a).

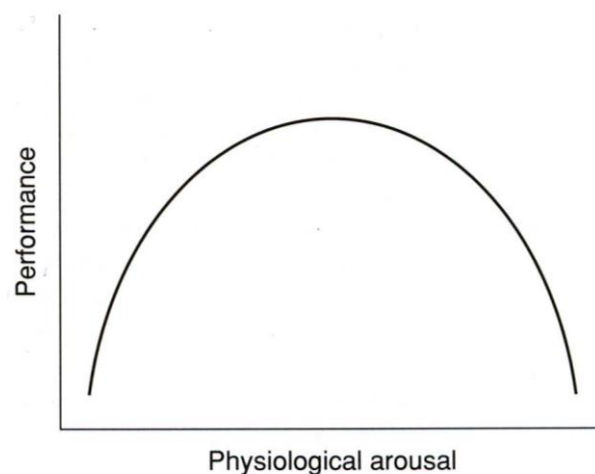
Two studies have previously quantified the attributes of rock climbers; Robinson (1985) measured the behavioural characteristics of elite rock climbers using: Zuckermans Sensation Seeking Scale (Zuckerman, 1979), Trait Anxiety Inventory (Spielberger, Gorsuch, & Lushene, 1970) and the Sports Behaviour Scale (Howe, 1976). Robinson (1985) reported that when data from the elite rock climbers was compared to normative data from Spielberger et al. (1970), trait anxiety was significantly ( $p < 0.01$ ) lower in elite climbers ( $33.52 \pm 7.98$  vs  $37.68 \pm 9.69$  respectively). Furthermore, the authors suggested that all respondents reported some degree of anxiety before attempting a hard route as well as during difficult sections of the ascent. Importantly, they also indicated that they felt able to cope with these feelings. In respect to lead climbing, 77% of respondents reported that they were willing to undertake long sections of unprotected climbing and 67% said they maintained self-control well, with only 13% reporting frequent anxiety whilst climbing. The range within the ability group used in the study may explain why some climbers (13%) reported frequent anxieties. Robinson (1985) described elite rock climbers in the study as lead climbing between 15 and 24 (Ewbank), and this range of grade brackets does not constitute elite rock climbers either in 1985 or the present-day. Furthermore, the authors do not suggest how the spread of abilities related to the degrees of anxieties reported.

Feher et al. (1998) attempted to resolve the issue of ability group categorisation, breaking down rock climbing participants' into 'moderate' graded 12 – 16 (Ewbank) and 'advanced' graded 16 – 33 (Ewbank). Although these grade brackets separate two groups of climbers, the large range of abilities within the advance group suggest it is far from homogenous. The physical and mental differences between participants who climb grade 16 and 33 (Ewbank) is considerable, and would undoubtedly have an effect on the psychological approach of a climber. Therefore, it is not surprising that when Feher et al. (1998) quantified trait and state anxieties in these groups ( $n = 57$ ), no differences between ability groups or genders were reported. However, it was suggested that advanced climbers tended to exhibit higher tension, depression, anger, confusion and total mood disturbance compared to moderate climbers, although these differences were not shown to be significant ( $p > 0.05$ ).

Differences in abilities may have a small effect on the psychological profile of rock climbers when comparing groups that have a narrow ability range. However, when attempting to describe or compare groups, a spread of more than four performance

grades (Ewbank), whether it is a self-reported top rope or lead climb, is quite substantial and could easily have a profound effect on the responses. For a climber who is notably more experienced, including exposure to difficult routes and/or a higher degree of success, falling and failure is likely to elicit a far different psychological response compared to a novice or inexperienced climber.

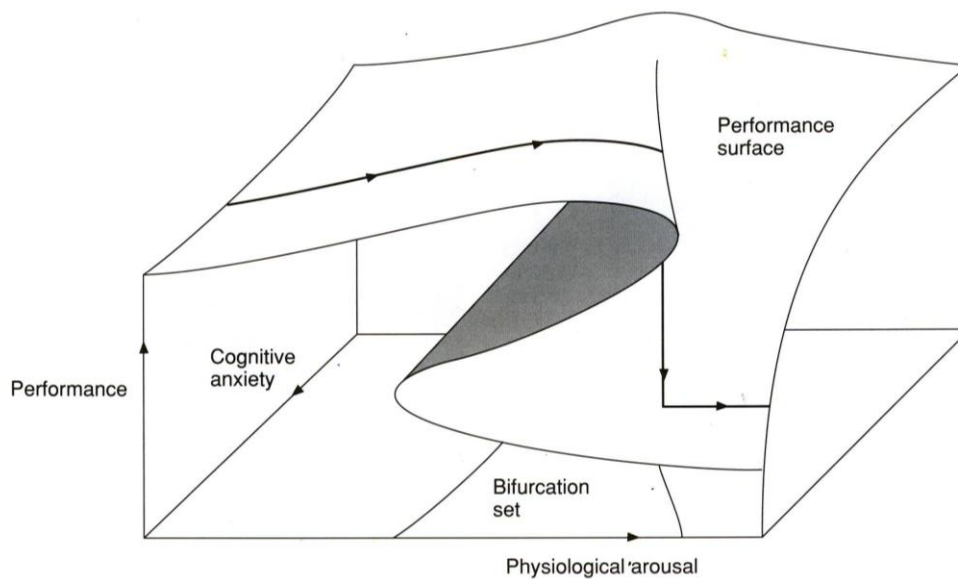
Yerkes and Dodson (1908) suggested that when arousal is increased, so is performance until a critical/optimal point is reached, at which performance begins to deteriorate (Figure 4.2). This model may be appropriate for many mainstream sports, as well as easy to moderate top rope and lead climbing, where the significance of failure is not so consequential. However, it might not be appropriate for modern day climbers ascending technically difficult and almost seemingly impossible competition routes. With well-known climbers such as Alex Honnald making some of the hardest ascents in the world un-roped and on-sighted, then surely performance does not teeter away as arousal increases. A decrease in performance within these situations will generally result in either significant injury or death. However, it is clear from the number of top level climbers partaking in these styles of ascents that the risk of a fall is a part of the sport, and that this is firmly understood and accepted. Elite climbers appear to have a very clear understanding and acceptance of what is perceived and real risk (Brown, 2012).



**Figure 4.2 Pictorial representation of the inverted-U hypothesis (Yerkes & Dodson, 1908).**

Although the inverted-U hypothesis has received empirical support from psychological researchers, it has also received much criticism (Horn, 2008). Landers (1980) suggested that the theory does not explain the relationship between performance and arousal, it simply highlights it as a curvilinear one, and pointed out that this relationship may not be true for numerous climbing based situations. A theory which allowed for the explanation and prediction with relation to the arousal/performance relationship was needed (Landers, 1980). Developed from the 'inverted-U hypothesis' came the catastrophe theory (Figure 4.3). The theory assumes there are two subcomponents of anxiety; cognitive anxiety and physiological arousal. Physiological arousal is based upon the sympathetic response system. However, it may also be reflected by other measures of somatic anxiety. Cognitive anxiety or the splitting factor arbitrates the effects of physiological arousal, and therefore may have a direct influence on performance (Horn, 2008). However, the three-dimensional model suggests that physiological arousal on the level of performance is mediated by cognitive anxiety. Consequently, the suggested relationship between performance and arousal will alter depending on the individual's levels of state cognitive anxiety, as well as trait anxiety.

It is suggested that the catastrophe component may occur only when cognitive anxiety is high (Horn, 2008). This may mean that an elite rock climber may elicit significant physiological changes to prevent a possible fall, such as increasing grip strength, but only when necessary, and when cognitive anxiety is very high. However, as previously mentioned elite rock climbers have managed to solo climbs that were once thought impossible with protection, routes such as Schleier (Austria) (32 Ewbank). It becomes clear that these individuals are able to deal with high levels of cognitive anxiety and prevent a catastrophe, such as a fall to certain death. Psychological adaptations or traits in these climbers, which may affect arousal, could also allow for a greater physiological control of some somatic mechanisms such as HR, breathing frequency and feelings of tension and nervousness.



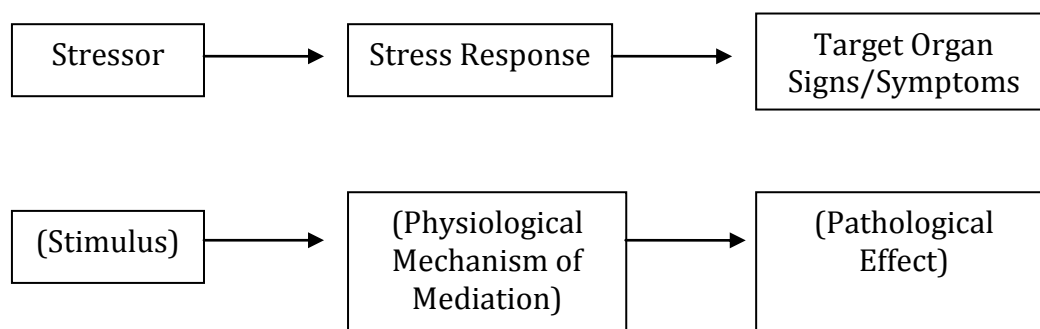
**Figure 4.3 A pictorial representation of the Catastrophe Theory (Hardy & Fazey, 1987).**

## 4.2 Psychophysiology in rock climbing

The interplay between the psychological profile and physiological function in humans has been of interest to scientists over the last 400 years (Fancher, 1996). One of the great achievements was the understanding of the effects of stress on the body. The term stress was first introduced to the allied health sciences in 1926 by Hans Selye (George Jr & Lating, 2002). As a second year student at the University of Prague, Selye noted a common constellation of symptoms in patients suffering a wide range of physical ailments. In his early writings he defines stress to be ‘the sum of all non-specific changes’ (Selye, 1956). More recently, his definition changed to ‘the non-specific response of the body to any demand’ (Selye, 1974). On a biochemical level the French scientist Claude Bernard has been acknowledged as the first author to recognise that the human body can alleviate the stress from the external environment due to cells within the body being able to maintain an internal homeostasis (Armstrong, 2000).

The human body aims to maintain a stable internal environment, balancing essential nutrients and chemicals at a ‘normal’ level. Stressors are influences that cause the body to be thrown out of homeostatic balance (Selye, 1956). When the body is exposed to a stressor, a series of short (accommodation), intermediate (acclimatisation) and long-

term (genetic) adaptations occur (Armstrong, 2000). These changes include most of the body's systems working together. However, the Central Nervous System (CNS) and 'stress' hormones such as nor epinephrine, epinephrine and cortisol also play a vital role. The acclimatisation (intermediate) phase of the stress response system involves an array of such adaptive responses, which are induced by alterations in the external environment such as those seen in sports like rock climbing. Figure 4.4 shows the stressor, stress response system and how the body adapts to deal with such external situations of stress.



**Figure 4.4 The stressor-stress response model (George & Lating, 2002).**

Physical and emotional stressors are antagonists for the secretion of corticotrophin, which in turn stimulates the anterior pituitary gland to release adrenocorticotrophic hormone (ACTH). This induces the adrenal cortex to discharge the hormone cortisol. Cortisol has many effects on bodily functions, such as decreased amino acid transportation into the cell, and stimulation of the breakdown of protein to building-block amino acids (in all cells except those in the liver) (McArdle, Katch, & Katch, 2009). The secretion of cortisol has been commonly used as a determinant of both emotional and physical stress (Chatterton, Vogelsong, Lu, & Hudgens, 1997; Goodyer, Park, Netherton, & Herbert, 2001; Richter et al., 1996).

Cortisol in the body is found in both free and bound forms. Previous studies have suggested that free cortisol accurately reflects hypothalamic-pituitary-adrenal (HPA) function when values are below  $500\text{nmol}\cdot\text{L}^{-1}$  (Putignano et al., 2001). However, above

500nmol·L<sup>-1</sup> a disproportionate rise in free cortisol (above the binding point of Corticosteriod binding globulin (CBG)) has been observed (Aardal & Holm, 1995; Kudielka, Schommer, Hellhammer, & Kirschbaum, 2004; Putignano et al., 2001). This disproportionate rise creates problems for studies which have used salivary cortisol as an assessment of stress in situations where there is a high degree of both psychological and physiological arousal. Bound cortisol (serum) may be a more accurate reflection of cortisol concentrations in these high stress evoking situations.

Chatterton et al. (1997) studied the hormonal responses to psychological stress in men preparing for skydiving. The study showed no significant differences between anxieties measured through psychological questionnaires on the morning of the dive compared to the control. However, hormonal measures showed that there was a significant difference in intensity, and sympathetic nervous system activity on the morning of the jump. This suggests that coping mechanisms such as the release of corticotrophin could increase sympathetic activity leading up to a jump in such a perceived high risk sport.

Unfortunately, the study did not measure the cortisol response post-stress, or parasympathetic activity, and so post-stress coping mechanisms cannot be assessed. The relative contributions of the sympathetic and parasympathetic systems would have provided a clearer understanding of the underlying mechanisms involved in the stress response systems throughout the activity. The authors concluded that purely psychological stress was suppressed until a few hours before the jump. However, this response was preceded by an elevation in sympathetic intensity and activity.

Cortisol has been used within numerous sporting and medical based assessments of psychological and physiological stress (Chatterton et al., 1997; Fink, 2000; Goodyer et al., 2001; Roy, Kirschbaum, & Steptoe, 2001; Schnabel, Kindermann, Steinkraus, Salas-Fraire, & Biro, 1984). Consequently, the study of cortisol can be used to investigate the interplay between psychological appraisal and its effects on the physiological mechanisms in rock climbers was considered appropriate. Remarkably only one known study has sought to use cortisol as a marker of the psychological stress response system in rock climbing. Hodgson et al. (2009) were interested in using cortisol as a measure of assessing psychological stress during different safety roped protocols in intermediate rock climbers. After a familiarisation climb, climbers (n = 12) completed a lead, a top rope and a lead on top rope climb in a randomised order. The CSAI-2R was assessed pre-climb, and blood samples for the assessment of bound

plasma cortisol were taken. The authors found that  $\Delta$  cortisol concentrations rose during the lead ascent (most stressful) and decreased during the top rope (least stressful) ascent. Furthermore, there was a significant moderate ( $R^2 = 0.425$   $p = 0.001$ ) cubic relationship between cognitive anxiety and cortisol concentration. There were also significant weak cubic relationships between plasma cortisol concentration and self-confidence ( $R^2 = 0.281$ ,  $p = 0.004$ ), as well as somatic anxiety ( $R^2 = 0.268$ ,  $p = 0.017$ ). The authors suggested that for intermediate climbers, lead climbing was the most stressful condition and top rope climbing was the least stressful, with top rope lead lying between the two. Lead climbing resulted in the highest levels of somatic anxiety and the lowest levels of self-confidence. Although the same pattern was seen for cognitive anxiety, the differences between conditions were not significant. It would appear that lead climbing elicits a heightened cortisol response in intermediate climbers. However, it should be noted that there was no mention of the time at which blood samples were collected from the participants, and therefore it is difficult to assess whether the authors had captured the highest concentration of the cortisol response.

There is no known research investigating the cortisol response in a range of different ability rock climbers during either a lead or a top rope climb. There is also a lack of research into the effects of rock climbing on the hormonal responses in all disciplines, styles and training methods for rock climbers. The few studies which have been conducted have only scratched the surface of our understanding of both the hormonal response and potential physiological and psychological interactions that may occur in rock climbers.

Although Hodgson et al. (2009) were the first authors to use cortisol as a measure of psychological stress in climbers they were not the only, or first authors to use cognitive or somatic anxieties along with physiological measures to assess the anxiety responses of rock climbers. As on-sight rock climbing is used within competition settings, and is generally considered a more pure ascent style than top rope climbing, it has received some attention. As previously mentioned, Draper et al. (2008) studied the effects of an on-sight lead climb compared to a secondary lead climb on the same sport route in intermediate ( $n = 10$ ) climbers. Climb time, BLa, HR,  $\dot{V}O_2$  responses and pre-climb cognitive and somatic anxieties as well as self-confidence were measured. There were significant differences between ascents for pre-climb cognitive and somatic anxieties, as well as a climb time and post-climb BLa concentrations. This study shows that



intermediate rock climbers may find on-sight lead climbing to be a more anxious-inducing than a subsequent lead climb

In a following study, Draper et al. (2010) considered the differences between a top roped and lead ascent, with regards to the psychological and physiological responses of intermediate climbers ( $n = 9$ ). Physiological measures consisted of HR,  $\dot{V}O_2$  and BLa concentration. Psychological measures of cognitive and somatic anxieties, as well as self-confidence and task load index were also assessed. The findings suggested that, compared to top rope, lead climbing elicited a significantly higher post-one minute ( $p < 0.05$ ) HR, and significantly higher BLa level immediately post and 15 minutes post-ascent, as well as a significantly longer climb time. There were no significant differences between top rope and lead ascents for self-confidence, somatic or cognitive anxieties, although the lead climbing was reported as being more physically and mentally demanding, requiring more effort and resulting in greater level of frustration ( $p < 0.05$ ). The authors suggested that the physiological demand for lead climbing was greater than top rope climbing, and that the additional energy demand was met by the anaerobic metabolism. Furthermore, it was suggested that the more technically demanding as well as physically (lead vs top rope) demanding a route is, the higher the BLa concentration. It would appear that when intermediate climbers are asked to on-sight a route there is an elevated anxious response. However, when there is existing knowledge of a route and an intermediate climber is asked to ascend on either a top rope or lead, there are no differences in anxiety levels. The lead appears to be physiologically harder and more frustrating. These combined findings suggest that for intermediate climbers, the most demanding and anxiety provoking style of ascent would be an on-sight lead climb.

#### **4.3 Summary and aims**

To date, there is evidence to suggest that intermediate rock climbers, when asked to on-sight a route at, or close to the top of their ability, may have increased levels of pre-climb somatic as well as cognitive anxieties. Furthermore, these increases in anxieties may affect the physiological responses during an ascent. There is evidence to suggest that in intermediate climbers the increase in these anxieties may elevate the contribution from the anaerobic metabolism during an ascent. However, there is no evidence to

suggest what the physiological and psychological demands of on-sight rock climbing are in any other ability group of rock climbers or the possible interaction between the two. No known research has been conducted on climbers who have a best on-sight grade of >18 (Ewbank). Therefore, the primary aims were: 1) to examine the psychological and physiological responses to difficult on-sight climbing with respect to ability level, and 2) examine the effects of ascent style (lead vs top rope) on the above responses.

#### **4.4 Hypotheses**

- H1: There will be an increased nervous response in intermediate rock climbers during the on-sight lead condition compared to the top rope.
- H2: The intermediate rock climbers will have a greater nervous response than all other ability groups.
- H3: There will be no psychological or physiological differences between the ascent styles for the elite and advanced climbers.

#### **4.5 Strength of the study**

- The current study is the largest known investigation into the physiological and psychological demands of rock climbing.
- The findings are specific to three distinct ability groups.
- All three routes were set by an experienced competition route setter on the same section of wall providing the same opportunity for clipping and rest periods.

#### **4.6 Limitations**

Although careful consideration has been given to the methods employed, and numerous pilot studies were conducted, there were still some limitations and delimitations within study one.

- It was assumed that at the time of recruitment the participants accurately self-reported their best on-sight and red-point grades.
- It was assumed that all participants refrained from alcohol 24 hours and caffeine 2 hours prior to testing sessions as requested.
- Elite climbers were classified as > 25 Ewbank and not > 29 as suggested in Appendix G. This was due to the lack of world class climbers in the greater Christchurch area.
- Although familiarisation climbs were conducted, the Cosmed K4b<sup>2</sup> [gas analysis] mask covered the mouth of the participant which may have altered the climbing/clipping style within the lead groups.
- Because each participant had to be lowered to the ground before blood samples could be taken, immediately-post samples represent samples taken within 15 seconds post-climb.
- All participants refrained from either inspecting or attempting the route prior to their testing session as requested.

#### **4.7 Delimitations**

- Findings of the current study are specific to the best on-sight grade of intermediate (18 Ewbank) advanced (22 Ewbank) and elite (25+ Ewbank) rock climbers.
- Findings are representative of both on-sight top rope and lead climbing at the top of each group's respective ability level.
- All data are specific to the route profile which was used for all graded climbs.

## Methods for Study One

The current chapter describes the equipment and procedures used to assess the variety of physiological and psychological aspects of on-sight rock climbing. This study employed a rock-climbing specific approach to examine potential differences in lead and top rope ascent styles across three distinct ability groups: intermediate, advanced and elite rock climbers. The subsections: *participants*, *route design*, *procedures*, *psychological measures*, *physiological measures*, *blood sampling*, *cortisol analysis*, *video analysis* and *statistical analysis* describe the methods used to achieve the fore mentioned research.

### 5.1 Participants

Participants were recruited from the four main climbing communities within the greater Christchurch area: the University of Canterbury Rock Climbing Club, the Lincoln University Alpine Club, the YMCA rock climbing gym and the Roxx climbing gym. In total 58 participants were recruited over a six month period. As the testing design was an on-sight attempt, participants were selected based on their self-reported best indoor on-sight grade (achieved within the past 12 months). A pilot study showed self-reporting grades (Appendix H) were an accurate self-assessment of indoor rock climbing ability. In order to have homogenous groups, a narrow bracket of two grades (Ewbank) was used to create the three ability groups: intermediate, advanced and elite. A pilot study (Appendix G) which involved communication with academics and climbing coaches was conducted in order to classify climbers into ability groups using their best self-reported on-sight grade. The groups recruited for this study were categorised as 18/19 (Ewbank) for intermediate, 22/23 for advanced and > 25 for elite.

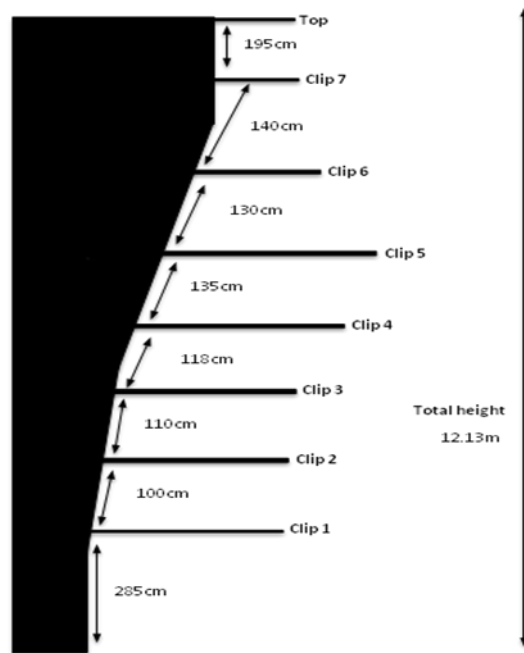
**Table 5.1 Mean  $\pm$  SD participant demographic and anthropometric data.**

	Intermediate		Advanced		Elite	
	Top rope (n=5)	Lead (n=7)	Top rope (n=9)	Lead (n=10)	Top rope (n=7)	Lead (n=5)
Years climbing	3.0 $\pm$ 1.2	3.2 $\pm$ 1.1	3.3 $\pm$ 1.1	3.4 $\pm$ 0.7	3.4 $\pm$ 0.8	3.8 $\pm$ 0.5
Climbs per week ***	1.7 $\pm$ 0.8	1.6 $\pm$ 0.6	3.2 $\pm$ 0.9	3.4 $\pm$ 1	3.6 $\pm$ 1	3.4 $\pm$ 0.9
Lead experience (yrs)	4.6 $\pm$ 3.9	9 $\pm$ 9.5	8.9 $\pm$ 10.9	8 $\pm$ 8.1	6.8 $\pm$ 6.1	6.5 $\pm$ 3.2
Age (yrs)	24.1 $\pm$ 3.5	32 $\pm$ 7.3	29.6 $\pm$ 11.6	25.3 $\pm$ 9.1	22.4 $\pm$ 5.3	22.4 $\pm$ 4.8
Gender	3F, 4M	5M	1F, 9M	2F, 7M	7M	5M
Height (cm)	176.1 $\pm$ 6.7	178.4 $\pm$ 4.3	176 $\pm$ 6.2	175.2 $\pm$ 8.9	175.7 $\pm$ 4.9	174.1 $\pm$ 6.1
Weight (kg) ***	73.1 $\pm$ 12.8	81.5 $\pm$ 13.8	67.9 $\pm$ 9.2	67.8 $\pm$ 10.4	68 $\pm$ 6.1	67 $\pm$ 8.8
Body fat (%) ***	17 $\pm$ 4.1	17.7 $\pm$ 5.6	11.9 $\pm$ 5.7	12.9 $\pm$ 4.1	9.2 $\pm$ 2.9	11 $\pm$ 2.8
$\dot{V}O_{2\max}$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	54.5 $\pm$ 12.2	53.2 $\pm$ 5.8	59.7 $\pm$ 8.2	52 $\pm$ 9.5	57.9 $\pm$ 2.5	60.1 $\pm$ 6.7
$\dot{V}O_{2\max}$ HR	192.4 $\pm$ 9.5	185.4 $\pm$ 14	190.6 $\pm$ 10.2	192.2 $\pm$ 10	194.1 $\pm$ 8.2	190.6 $\pm$ 8.1

\*\*\* The intermediate group was significantly different ( $p < 0.05$ ) from the elite and advanced groups (top rope and lead combined)

## 5.2 Route design

In order to make accurate and reliable comparisons, the intermediate (18 Ewbank), advanced (22 Ewbank) and elite (25 Ewbank) routes were set at the top of the respective grade abilities. However, as previously mentioned, due to the limited number of world class climbers in the local area who could on-sight the grade of > 29 (Ewbank), the elite boundary and route was lowered from that suggested by Draper et al. (2009) to > 25 (Ewbank). Test routes were set by an experienced professional competition route setter, and were subsequently climbed and checked (including grade and style) by expert semi-professional climbers ( $n = 4$ ). All routes used a similar mix of sloping and crimping modular holds (Uprising Ventures Ltd, Canterbury, NZ) on a 12.31m high indoor wall (Sheer Adventure, Christchurch, Canterbury, NZ). All routes were set on the same section of wall so the profiles could be evenly matched. Each route was designed to provide similar clipping positions and rest opportunities throughout each ascent. The routes had 7 pre-placed quick draws. For the purpose of this study each quick draw will be referred to as a ‘clip’. The wall profile and distance between clips is presented in Figure 5.1.



**Figure 5.1 Climbing wall profile and clip spacing for the intermediate, advanced and elite routes.**

### 5.3 Procedures

Data collection for this study was broken down into three testing sessions, as shown in Figure 5.2. Session one was conducted at the University of Canterbury's Exercise Physiology Laboratory and sessions two and three were at an indoor climbing gym (The Roxx, Christchurch, NZ). As diurnal variation has been shown to significantly alter resting levels of cortisol concentration (Hruschka, Kohrt, & Worthman, 2005), each participant's sessions were conducted at the same time of day. The individuals three testing sessions were separated by no less than 72 hours and no more than 10 days. For each session participants were asked not to consume alcohol 24 hours prior, and caffeine or large meals for at least two hours prior to testing. Individuals were asked not to alter their training regime in the days leading up to each session. Furthermore, participants were asked not to perform strenuous exercise for the 12 hours leading up to each visit. All participants were fully acquainted with the nature of the study and informed that they could leave at any stage. Before taking part in the current study all participants completed a medical health history questionnaire and gave written informed consent. Ethical approval was granted by the University of Canterbury's Human Ethics Committee (HEC 2010/5).

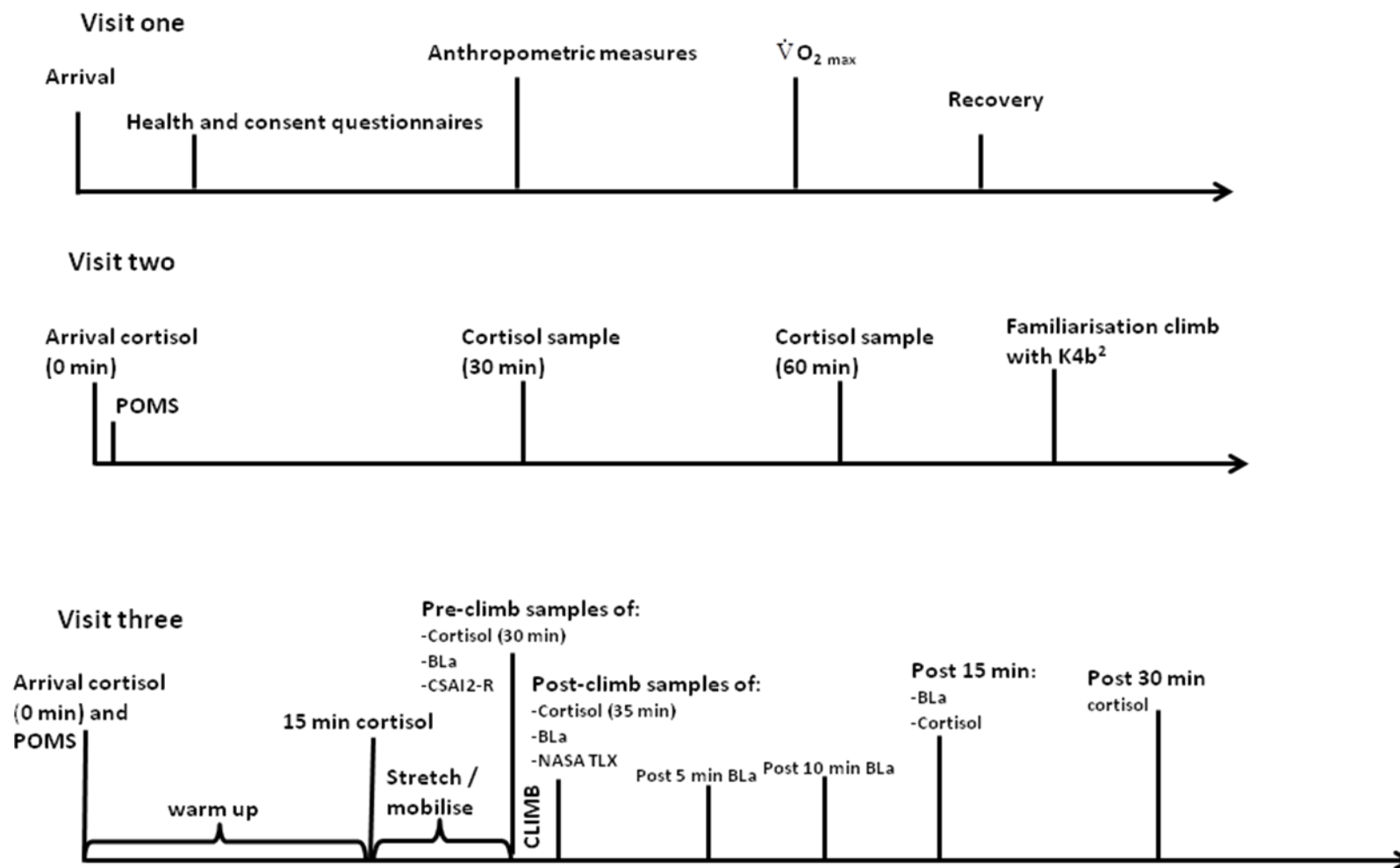


Figure 5.2 Schematic of the testing protocols for visits one, two and three.

### **5.3.1 Baseline data**

All baseline data for the current study was collected in the first two testing sessions. Session one was conducted at the University of Canterbury's Exercise Physiology Laboratory and was used to collect anthropometric and physiological data. Session two was conducted at the climbing gym, and was designed to measure mood state, collect resting blood cortisol samples for subsequent cortisol analysis and allow participants to familiarise themselves with climbing whilst wearing the K4b<sup>2</sup> metabolic system.

### **5.3.2 Session one**

Anthropometric measures (Table 5.1) were collected and a treadmill (Woodway<sup>®</sup>, Waukesha, Wisconsin, USA) based  $\dot{V}O_{2\max}$  was conducted. Anthropometric measures consisted of assessing body composition (bio impedance analysis (Body Stat, Korea)), mass and height (stadiometer).

Maximal  $O_2$  consumption was assessed using the athlete led protocol (ALP) (Draper & Marshall, 2013). The ALP starts with the participant running at 8km/HR with 0% gradient; at the end of every minute the speed was increased by 1km until the participant indicated he or she had reached their maximum cadence. From here the treadmill gradient was increased by 1% every minute until exhaustion. Maximal  $O_2$  consumption was measured using a portable metabolic system (K4b<sup>2</sup> Cosmed, Rome, Italy), and data was averaged at 15s intervals.

### **5.3.3 Session two**

Session two was designed so that mood state could be assessed and blood samples could be collected for subsequent cortisol analysis. On arrival at the climbing gym all participants were asked to fill out a Profile of Mood States (POMS) questionnaire. Once the POMS questionnaire was completed, the participant's foot was bathed in warm water for a two minute period to increase blood flow (BF) to the toe. Subsequently the foot was dried and cleaned with an alcohol wipe. The first 300 $\mu$ L capillary blood sample was taken (0 minutes), followed by one at 30 minutes, and a final sample at 60 minutes post-arrival. Once all three blood samples were taken, the participants were



informed about their familiarisation climbs (minimum of two climbs). This was done after blood sampling so that the prospect of climbing whilst wearing the metabolic system did not affect resting cortisol concentrations.

#### **5.3.4 Session three**

The third and final session took place at the climbing gym. Upon arrival a capillary blood sample (300 $\mu$ L) was taken (0 minutes) for subsequent analyses of cortisol concentration. The participant was then informed of the grade of climb (18 intermediate, 22 advanced and 25 elite (Ewbank)) and their ascent style (lead or top rope). Climbers completed a specific warm-up consisting of five minutes light jogging (60% of HR max), a warm-up top rope climb of their choice (two grades below their best on-sight grade) and five minutes of stretching and mobilising. Following the warm-up a second capillary blood sample (300 $\mu$ L) was collected (15 minutes post-arrival). The climber was then fitted with the K4b<sup>2</sup> metabolic system and given time to inspect the route whilst continuing to stretch and mobilise. Before attaching themselves to the rope, BLA concentration was sampled along with capillary blood (pre-climb (30 minutes post arrival)) for cortisol analysis. Once the climber was attached to the rope they filled in a CSAI-2R questionnaire to measure pre-climb cognitive and somatic anxieties, as well as self-confidence. During the climbing trial HR and  $\dot{V}O_2$  were recorded continuously using a K4b<sup>2</sup> metabolic system. Immediately after completing the climb a NASA – TLX (Hart & Staveland, 1988) questionnaire was completed. Blood lactate and capillary blood (for subsequent cortisol analysis (post-climb at approximately 35 minutes post-arrival)) were sampled immediately on contact with the ground. A 30 minute recovery period was started during which BLA concentration was sampled at 5, 10 and 15 minutes post-climb. Capillary blood samples for subsequent cortisol analyses were also collected 15 and 30 minutes post-climb.

#### **5.4 Psychological measures**

Psychological assessments were used for three main purposes within the current study:

- 1) to determine whether affective mood state fluctuated between the baseline session (visit 2) and climbing session (visit 3),
- 2) to determine levels of pre-climb cognitive and

somatic anxieties as well as self-confidence, and 3) to measure the physical and mental task effort that was perceived during the climbing ascents.

#### **5.4.1 *Profile of Mood States***

In order to assess mood state the shortened POMS questionnaire was administered during visits two and three. The self-administered questionnaire has been shown to highlight changes in both acute treatments and effects (McNair, Lorr, & Droppleman, 1981). Furthermore, it has been validated in both adult (Nyenhuis, Yamamoto, Luchetta, Terrien, & Parmentier, 1999) and adolescent populations (Terry, Lane, Lane, & Keohane, 1999).

#### **5.4.2 *Competitive State Anxiety Inventory – Revised***

The CSAI-2R has been extensively used within sport science research (Cox, Martens, & Russell, 2003; Jordet, Elferink-Gemser, Lemmink, Visscher, & Button, 2006; Terry, Lane, & Shepherdson, 2005). The questionnaire has been used to provide a profile of a person's level of cognitive and somatic anxieties, as well as levels of self-confidence at the time the questionnaire is being filled in. The questionnaire has previously been used in several rock climbing studies (Draper et al., 2008; Draper et al., 2010; Hodgson et al., 2009).

#### **5.4.3 *National Aeronautics and Space Administration – Task Load Index***

The NASA-TLX is a short self-administered questionnaire that has been widely used throughout sport as a subjective measure of effort and task difficulty (Capa, M, & S, 2008; DiDomenico & Nussbaum, 2008; Schnitzler, Ernwein, & Chollet, 2006; Tomporowski & Ganio, 2006). The NASA-TLX has been used in one rock climbing study (Draper et al., 2010), as it provides an understanding of participants overall task difficulty. This is considered more appropriate for the current study, compared to the Borg Scale which focuses mainly on the rate of perceived exertion (Borg, 1982) and not factors such as fatigue, temporal demands or level of frustration.

## 5.5 Physiological measures

### 5.5.1 *Heart rate and oxygen consumption*

As suggested by Özyener, Rossiter, Ward, and Whipp (2011) the breath-by-breath data was screened to eliminate occasional false breaths, for example, those triggered by swallowing, coughs or sighs. These were considered to be uncharacteristic of the underlying physiological responses and could cause abnormalities within the data. Both HR and  $\dot{V}O_2$  have been reported as total climb averages.

### 5.5.2 *Blood sampling*

Capillary blood was sampled to assess bound plasma cortisol concentration. A pilot study had shown that over a large range of concentrations, post-exercise capillary concentrations had close agreement with samples collected from venous blood (Appendix F). Assessing plasma cortisol and BLa concentration from the fingertip has been widely used in previous rock climbing studies (Billat et al., 1995; Booth et al., 1999; Watts and Drobish 1998; Draper et al., 2008; Hodgson et al., 2009; Draper et al., 2010). However, piercing the fingertip with a Haemolance 1.6mm blade is not appropriate in a climbing context, as a high load is placed on the fingertips during an ascent. Furthermore, ascending with a pierced fingertip and wearing a plaster during an on-sight attempt, may cause unnaturally heightened levels of anxiety, as well as altering the dynamics of the climb. Therefore, all capillary blood samples in this study were collected from the first (big) toe in-order to minimise the possible effects on climbing performance. A pilot study showed close agreements between the toe and the fingertip for the circulation bound cortisol concentrations both pre and post-rock climbing (Appendix I). Furthermore, the same close agreement was found for BLa concentration pre and post-rock climbing (Appendix E).

Before capillary blood sampling took place, the foot was bathed in warm water to increase BF to the area. Following this the foot was dried and the toe prepared using a non-alcoholic medical wipe (TYCO Healthcare, UK) before a haemolance plus (Haemedic, Poland) was used to puncture the site to a depth of 1.6mm. Blood lactate concentration was analysed using the portable Lactate Pro instrument (Arkray Inc,

Kyoto, Japan). Blood samples (300 $\mu$ L) for subsequent cortisol analysis were collected in a lithium heparin CB300LH Microvette (Sarstedt Aktiengesellschaft & Co, Germany) before being immediately spun in a cr2000 centrifuge (Centurion Scientific, England) at 10,000 rpm for 10 minutes. Once the blood was separated, plasma was extracted and stored in Eppendorf microtubes (Sarstedt Aktiengesellschaft & Co, Germany) at -20°C for subsequent analysis.

## **5.6 Cortisol analysis**

Blood plasma was analysed for bound cortisol concentration using an enzyme-linked immunosorbent assay (ELISA) procedure which had been previously validated by Lewis and Elder (1985) (Dept of Clinical Biochemistry, Christchurch Hospital, New Zealand). The ELISA method involves fixing an unknown amount of antigen to the surface of a well or plate. A specific antibody was then applied to the surface of this well so that it could attach to the antigen. This antibody was directly linked to a specific enzyme, the substrate for this enzyme was subsequently added to the plate and the reaction caused a change in colour. This colour was read by a Fluro plate reader and provided an accurate concentration, in this case cortisol concentration from blood plasma. The ELISA method used in the current study involves several stages: coating the plate, blocking the plate and setting up a standard curve, constructing the antibody, incubation and plate reading.

### **5.6.1 Coating the plate**

Coating the plate consisted of making up a 10mL coating solution per plate (Falcon Plate 3912, Microtest III Becton, Dickinson, USA) by mixing 5 $\mu$ L of cortisol-thyroglobulin conjugate (well mixed as it is a precipitate) with 10mL of guanidine hydrochloric acid (HCl) in a glass beaker. Coating solution (100 $\mu$ L) was then added to each well of every plate using an Eppendorf multi-channel pipette (Eppendorf, Hauppauge, New York, USA). The plates were then stored overnight to allow sufficient binding to take place.

### **5.6.2    *Blocking the plate and setting standards***

All wells were emptied to remove the coating solution. The plate was then blotted ensuring no foreign objects entered the wells. The plate was rinsed four times with washing solution. Each well was blocked by adding assay buffer (150 $\mu$ L per well) and incubated for 30 minutes. Standards were included at 0, 175, 350, 700, 1400 and 2800 nmol·L<sup>-1</sup> concentrations. Once each well was emptied of blocking buffer, 45 $\mu$ L of the appropriate standard was dispensed into each well (in duplicate wells). Zero plasma (human plasma stripped of cortisol (5 $\mu$ L)) was then added to each well. To set up the wells containing the participant's samples, 10mL of assay buffer was added to two drops of bromocresol purple indicator. Then 45 $\mu$ L of this combined solution was added to each well.

### **5.6.3    *Antibody construction and incubation***

Following the addition of the unknown cortisol, the monoclonal antibody was prepared. This monoclonal antibody was created by mixing the first and second antibodies together at a ratio of 1:25 (total: 200 $\mu$ L), then adding this to 7mL of assay buffer and 14 $\mu$ L of goat anti-mouse horseradish peroxidase (HRP) (Chemicon, USA). Then 50 $\mu$ L of this solution was added to each well, and incubated for 45 minutes at room temperature. After incubation the plate was washed four times and 100 $\mu$ L of tetramethylbenzidine (TMB) substrate was added. Once the plate had turned blue, the reaction was stopped using 100 $\mu$ L of 0.9mol HCl. Plate absorbency was read at 450nm using a FLUO star OPTIMA (BMG, LabTech, Germany). All standards, controls and samples were analysed in duplicate. Intra assay coefficients of variation were < 10% (**Error! Reference source not found.**). Cortisol concentrations were expressed as nmol·L and were subsequently converted to ng·mL with a factor of 27.59 (Volovitz, Kauschansky, Nussinovitch, Harel, & Varsano, 1995).

### **5.6.4    *Depicting psychological and physiological components of cortisol***

In order to depict the psychological and physiological component of the cortisol response in different ability groups for top rope and lead ascents,  $\Delta$  cortisol responses were calculated. Delta cortisol for the psychological component was determined by

subtracting the final baseline (60 minute) sample from the pre-climb sample. Delta cortisol responses for the physiological component of the on-sight climbs was determined by subtracting the post 15-minute climb sample from the pre-climb sample. The time periods used to determine the  $\Delta$  scores were chosen due to the diurnal variations in cortisol (Hruschka et al., 2005; Levine et al., 2007), and the time points during the testing sessions which were believed to elicit the highest responses of either physiological function or psychological stress (Smyth et al., 1998).

### 5.7 Video analysis

Each climb was recorded using a high definition digital video recorder (Canon Legria, HF20 HD). Time spent in a static position was calculated by adapting the technique described by Billat et al., (1995). The authors suggested that a static position on the wall denoted time spent in isometric contraction. This static position was defined as any point throughout the climb where the hips were not in motion. However, as static time is often used by climbers to rest, shake out, and make tactical decisions, both static time and rest time (s) were recorded.

For the purpose of this study:

A **rest** was defined as a period of time where one hand left the wall to be *flicked*, *stretched* or *shaken out*. If the participant rested one hand and then the other without ascending further up the wall, then each individual hand rest was counted separately.

**Rest time** in seconds was the culmination of all rest periods seen in a single ascent.

**Static time** was defined as any period where the participant's hips were not actively ascending the wall.

**Percentage of static time which was spent resting** was determined by dividing the *total rest time* by the *total static time* and then multiplying the number by 100.

## 5.8 Statistical analysis

All analyses were performed using Statistical Package for Social Sciences (SPSS, Version 19.0, Chicago, IL) and Microsoft Excel (2007). All data is presented as mean  $\pm$  SD unless otherwise stated. For all analysis the critical  $\alpha$ -level was set at 0.05.

Bonferoni correction error was used for multiple comparisons. All variables were assessed for normality of distribution using the one-sample Kolmogorov-Smirnov goodness-of-fit test as well as checking for equal variance by visually examining the variance around the mean on box plots (if the maximum variance was less than three times the minimum variance, then equal variance was assumed). This is the normal accepted rule to determine whether the analysis of variance (ANOVA) test is reliable. For each independent variable a series of analysis of covariance (ANCOVA) were performed, the covariates were: height, weight, age, skeletal muscle mass and body fat percentage. None of the covariates were found to significantly affect any of the independent variables. Therefore, we reverted to using ANOVA for each variable of interest. To control the increasing error rate due to multiple testing with several independent variables, a global multi analysis of variances (MANOVA) tested for a difference in means across all groups. In all cases where a significant MANOVA test statistic was found, ANOVA was used to assess differences in each independent variable. Bonferroni correction for ANOVA was determined by multiplying the  $p$  statistic by the number of independent variables entered into the MANOVA. If it remained less than 0.05 then it was considered statistically significant. Post-hoc least significant difference (LSD) tests or  $t$ -tests were used to explore the source of the differences in the means between groups for each significant ANOVA, whilst controlling for the error rate. For all  $t$ -tests Bonferoni correction was used ( $p$  statistic multiplied by the number of tests) to determine the adjusted  $p$  statistic. Confidence intervals were calculated for the LSD and  $t$ -tests and were reported at 95%.

### 5.8.1 Physiological and psychological analysis

To determine if there were differences between ability groups and ascent styles on the combined independent variables, a series of one and two-way MANOVA's were conducted on the following four groups of data: POMS (section 6.2.1), pre and average-climb HR and  $\dot{V}O_2$  responses (6.2.2 and 6.3.2), CSAI-2R (6.2.3) and BLa (6.3.3). Where significant differences were found between the ability groups, ascent styles or

the interaction effect, a series of one or two-way ANOVA's, as well as a three-way repeated measures ANOVA (BLa concentrations only) were used. Where significant differences between groups were found, subsequent post-hoc analyses, LSD or independent *t*-test models were conducted to determine where the differences were.

### **5.8.2 Movement analysis**

Before exploratory analysis was performed on data interpreted from the video, 20% of all climbing videos (intermediate *n* = 3, advanced *n* = 4, elite *n* = 4) were assessed by a professional rock climber (observer two). Limits of agreement plots were created to explore any difference or bias between observers one and two.

All movement data showed close asymmetry and so all variables were log transformed so that assumptions of ANOVA were not confounded. As all the movement variables were related a two-way between groups MANOVA (section 6.4.1) was used to determine if there were potential differences between ability groups and ascent styles as well as a possible interaction effect. Following this a series of one-way and two-way ANOVA's were used to examine differences in: *rest frequency*, *average rest time*, *static time* and *percentage of static time which was spent resting*. Where significant differences were found, appropriate post-hoc LSD tests were used to determine where the differences lay.



## **5.9 Summary**

The majority of previous research which has investigated the physiological responses during rock climbing has speculated about the psychological effects of the climber during the ascent. The effects of the potential anxiety based nervous interactions on the physiological responses during investigations into rock climbing pose numerous issues for researchers and should not be ignored or merely speculated upon. The method presented here attempts to clearly and reliably separate the psychological and physiological responses during on-sight lead and top rope rock climbing. Specific attention has been paid to ensure the ability groups have a narrow best on-sight grade bracket, and that the respective routes are set accordingly. Furthermore, in order to accurately compare between ability groups, the route profiles were clearly matched to ensure similar opportunities were provided for clipping and resting. The following chapter 'Results for Study One' presents the data with appropriate statistical analyses to ensure valid interpretations can be made with regards to the psychological and physiological components of on-sight rock climbing.

## Results for Study One

### 6.1 Participants

Table 6.1 provides details of the number of climbers which completed and fell whilst on-sight climbing the test route. The participants which fell were excluded from all analyses. The groups intermediate, advanced and elite were matched and then randomly assigned to top rope and lead groups. Groups were subsequently checked for balance across age, gender, best on-sight and best red-point grade (as presented in Table 5.1).

**Table 6.1 Distribution of participants who fell and completed whilst top rope and lead climbing the test route.**

		Fell	Completed
Intermediate (n = 20)	Top rope	3	5
	Lead	5	7
Advanced (n = 23)	Top rope	3	9
	Lead	1	10
Elite (n = 15)	Top rope	2	7
	Lead	1	5

### 6.2 Pre-climb

The following section describes both the physiological and psychological responses that occurred immediately before a climb took place on either top rope or lead.

#### 6.2.1 Profile of Mood States

A POMS questionnaire was used to measure and assess potential differences in mood state on arrival at both the baseline (session two) and climbing trial (session three).

Table 6.2 presents mean  $\pm$  SD, as well as  $F$  and  $p$  values (two-way ANOVA, interaction effect) for all the responses within the questionnaire during sessions two and three.

Mean  $\pm$  SD, and statistical analysis suggests there were no differences in mood states between sessions, or ability groups and ascent styles.

**Table 6.2 Mean  $\pm$  SD responses to the Profile of Mood States questions for all ability groups and ascent styles.**

POMS Questions	Intermediate		Advanced		Elite		<i>F</i> value df 2,36	<i>p</i> value
	Top rope	Lead	Top rope	Lead	Top rope	Lead		
Baseline								
<i>Fatigue</i>	0.6 ± 0.9	1.1 ± 0.5	1.3 ± 0.6	1.5 ± 0.9	1.1 ± 1	0.8 ± 0.5	0.840	0.440
<i>Anger</i>	0 ± 0	0.1 ± 0.1	0.2 ± 0.3	0.3 ± 0.6	0.1 ± 0.9	0 ± 0	0.153	0.859
<i>Tension</i>	0.7 ± 0.3	0.5 ± 0.4	0.8 ± 0.4	1 ± 0.4	0.6 ± 0.3	0.5 ± 0.4	1.364	0.268
<i>Depression</i>	0.7 ± 0.2	0.1 ± 0.1	0.2 ± 0.3	0.3 ± 0.5	0.1 ± 0.9	0.1 ± 0.2	0.199	0.821
<i>Vigour</i>	2 ± 0.8	2.3 ± 0.4	1.8 ± 0.6	2 ± 0.9	2 ± 0.6	1.6 ± 0.6	1.019	0.371
Climb								
<i>Fatigue</i>	0.8 ± 0.6	1.3 ± 1.4	1.3 ± 0.5	1.5 ± 1.2	0.9 ± 0.7	0.8 ± 0.7	0.295	0.747
<i>Anger</i>	0.3 ± 0.7	0.3 ± 0.6	0.03 ± 0.1	0.1 ± 0.1	0.4 ± 0.9	0.1 ± 0.2	0.063	0.939
<i>Tension</i>	0.9 ± 0.5	0.8 ± 1.1	0.9 ± 0.5	1 ± 0.7	0.5 ± 0.3	0.7 ± 0.5	0.146	0.865
<i>Depression</i>	0.3 ± 0.5	0.3 ± 0.6	0.1 ± 0.2	0.3 ± 0.4	0.1 ± 0.1	0.1 ± 0.2	0.365	0.696
<i>Vigour</i>	2.2 ± 1	2.3 ± 0.5	1.9 ± 0.8	1.8 ± 0.9	2.3 ± 0.8	1.8 ± 0.9	1.432	0.252

*F* and *p* values are from the interaction effect (ability groups vs ascent style)

A two-way between groups MANOVA was performed to investigate ability group and ascent style differences in responses from the POMS questionnaire. The group responses to each individual question were used as the dependent variables. The independent variables were the ability group and ascent style. There was a non-significant interaction effect between ascent style and ability group on the combined dependent variables ( $F_{(20,56)} = 0.462$ ,  $p = 0.970$ ; Pillai's Trace 0.283). Furthermore, there were no significant differences for both the main effects, ability group ( $F_{(20,56)} = 1.241$ ,  $p = 0.258$ ; Pillai's Trace 0.614) and ascent style ( $F_{(10,27)} = 0.254$ ,  $p = 0.986$ ; Pillai's Trace 0.086).

To investigate differences in responses to the POMS questionnaire between the sessions two (baseline) and three (climbing test), a series of paired samples *t*-tests were conducted. There were no significant differences between sessions for: fatigue ( $t_{(41)} = 0.095$ ,  $p = 0.925$ ), anger ( $t_{(41)} = 0.059$ ,  $p = 0.953$ ), tension ( $t_{(41)} = 0.966$ ,  $p = 0.340$ ), depression ( $t_{(41)} = 0.113$ ,  $p = 0.911$ ) or vigour ( $t_{(41)} = 0.419$ ,  $p = 0.677$ ).

### 6.2.2 Pre-climb oxygen consumption and heart rate responses

Table 6.3 suggests that pre-HR for both lead and top rope ascents increased with ability group. However, pre top rope, the advanced group elicited only marginally higher responses than the intermediate group. For both intermediate and advanced groups the lead condition elicited a higher pre-climb HR than top rope. The elite group had a higher pre-climb HR than all other groups for both lead and top rope ascents.

For the top rope ascent, pre- $\dot{V}O_2$  responses were similar between all ability groups. However, for the lead climb, the pre- $\dot{V}O_2$  response was highest in the intermediate group, whereas the advanced group had the lowest response. With the exception of the intermediate group, all top rope climbs elicited a higher pre- $\dot{V}O_2$  response than the lead climbs. However, it should be noted that the above mentioned differences are minimal for both HR and  $\dot{V}O_2$ .

**Table 6.3 Mean  $\pm$  SD pre-climb heart rate and oxygen uptake responses in all ability groups and ascent styles.**

	Intermediate	Advanced	Elite	<i>F</i> value df 2,37	<i>p</i> value
TR HR (bts·min <sup>-1</sup> )	116.43 $\pm$ 7.93	117.8 $\pm$ 16.34	132.7 $\pm$ 14.4	0.073	0.929
LD HR (bts·min <sup>-1</sup> )	119.2 $\pm$ 20.74	127.63 $\pm$ 23.1	131.8 $\pm$ 15.56		
Combined	117.58 $\pm$ 13.89	122.17 $\pm$ 19.64	132.33 $\pm$ 14.19		
TR $\dot{V}O_2$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	14.68 $\pm$ 4.7	16.1 $\pm$ 3.75	16.44 $\pm$ 6.63	3.087	0.060
LD $\dot{V}O_2$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	17.26 $\pm$ 3.43	9.2 $\pm$ 3.73	12.71 $\pm$ 2.95		
Combined	15.76 $\pm$ 4.25	12.65 $\pm$ 5.07	14.88 $\pm$ 5.55		

*F* and *p* values are from the interaction effect (ability groups vs ascent style)

HR = heart rate,  $\dot{V}O_2$  = volume of oxygen, TR = top rope, LD = lead

A two-way between groups MANOVA was performed to investigate ability group and ascent style differences in the HR and  $\dot{V}O_2$  responses during all on-sight rock climbing ascents. Four dependent variables were used: pre-HR, average HR, pre- $\dot{V}O_2$  and average  $\dot{V}O_2$ . The independent variables were ability group and ascent style. There was a non-significant interaction effect between ascent style and ability group on the combined dependent variables ( $F_{(8,58)} = 0.927$ ,  $p = 0.501$ ; Pillai's Trace 0.227). There was also a non significant difference for main effect ascent style ( $F_{(4,28)} = 1.346$ ,  $p = 0.278$ ; Pillai's Trace 0.161). There was a significant difference for the main effect ability group ( $F_{(8,58)} = 2.385$ ,  $p = 0.027$ ; Pillai's Trace 0.495). A follow-up two-way ANOVA found that these differences were for the dependent variables

average HR and average  $\dot{V}O_2$  (as described later in section 6.3.2), and not any pre-climb data.

### 6.2.3 Pre-climb Competative State Anxiety Inventory – Revised

Mean  $\pm$  SD in Table 6.4 suggest that differences both within and between all ability groups for levels of somatic and cognitive anxieties as well as self-confidence were minimal. Levels of pre-climb somatic anxiety marginally decreased as ability level increased across the groups.

**Table 6.4 Mean  $\pm$  SD pre-climb somatic and cognitive anxieties as well as self-confidence in all ability groups and ascent styles.**

	Intermediate	Advanced	Elite	<i>F</i> value df 2,36	<i>p</i> value
Somatic anxiety					
TR	18.57 $\pm$ 2.78	16.43 $\pm$ 2.95	15.1 $\pm$ 4.87	0.216	0.807
LD	16.57 $\pm$ 2.78	16.19 $\pm$ 3.98	14.57 $\pm$ 4.21		
<i>Combined</i>	17.66 $\pm$ 2.5	16.32 $\pm$ 3.38	14.88 $\pm$ 5.55		
Cognitive anxiety					
TR	14.67 $\pm$ 3.7	15.8 $\pm$ 3.05	15.14 $\pm$ 4.88	0.278	0.759
LD	16.8 $\pm$ 5.4	17.56 $\pm$ 5.55	14.8 $\pm$ 3.03		
<i>Combined</i>	15.64 $\pm$ 4.46	16.63 $\pm$ 4.37	15 $\pm$ 4.05		
Self confidence					
TR	30.57 $\pm$ 7.18	25.8 $\pm$ 6.89	29.7 $\pm$ 7.43	0.749	0.480
LD	30.4 $\pm$ 4.98	25.78 $\pm$ 4.52	24 $\pm$ 6.33		
<i>Combined</i>	30.5 $\pm$ 6.1	25.79 $\pm$ 5.73	27.3 $\pm$ 7.4		

*F* and *p* values are from the interaction effect (ability groups vs ascent style)

TR = top rope, LD = lead

A two-way between groups MANOVA was performed to investigate ability group and ascent style (lead vs top rope) differences in pre-climb anxieties for all top roped and lead ascents. Three dependent variables were used: Pre-climb cognitive and somatic anxieties, as well as self-confidence. The independent variables were ability group and ascent style. There was a non-significant interaction effect between ascent style and ability group on the combined dependent variables ( $F_{(6,70)} = 0.580$ ,  $p = 0.745$ ; Pillai's Trace 0.095). Furthermore, there were no significant differences for both the main effects ability group ( $F_{(6,70)} = 1.590$ ,  $p = 0.163$ ; Pillai's Trace 0.240) and ascents style ( $F_{(3,34)} = 1.321$ ,  $p = 0.284$ ; Pillai's Trace 0.104).

#### 6.2.4 *Delta cortisol concentrations (psychological component)*

The mean  $\pm$  SD  $\Delta$  cortisol concentration for the psychological component of on-sight climbing suggest that in all ability groups the top rope ascent provoked a higher response compared to the lead. Furthermore, concentrations were the lowest in advanced climbers, whereas both the intermediate and elite groups elicited similarly higher responses. The mean and the large SDs presented in Table 6.5 suggest there were no differences in  $\Delta$  cortisol concentrations between ability groups or ascent styles.

**Table 6.5 Mean  $\pm$  SD delta cortisol concentrations (psychological component) for all ability groups and ascent styles.**

	Intermediate	Advanced	Elite
Top rope $\Delta$ cortisol (ng·mL)	54.84 $\pm$ 60.75	10.92 $\pm$ 30.04	45.67 $\pm$ 63.1
Lead $\Delta$ cortisol (ng·mL)	33.64 $\pm$ 15.7	4.1 $\pm$ 34.28	25.88 $\pm$ 33.97
<i>Combined <math>\Delta</math> cortisol (ng·mL)</i>	<i>46 <math>\pm</math> 47.13</i>	<i>7.53 <math>\pm</math> 31.47</i>	<i>37.42 <math>\pm</math> 51.89</i>

$\Delta$  = delta score

A two-way ANOVA revealed there was a non-significant interaction effect between ability group and ascent style ( $F_{(2,42)} = 0.124$ ,  $p = 0.884$ ). There was also a non-significant difference for both the main effects ability group ( $F_{(2,42)} = 2.937$ ,  $p = 0.066$ ) and ascent style ( $F_{(1,42)} = 1.334$ ,  $p = 0.256$ ). To further investigate the cortisol psychological component of top rope and lead climbing both within and between ability groups, linear regression analyses were conducted for  $\Delta$  cortisol responses and pre-climb somatic and cognitive anxieties as well as self-confidence. No significant ( $p < 0.05$ ) linear relationships were observed in any ability groups or ascent styles for  $\Delta$  cortisol concentrations, and pre-climb somatic or cognitive anxieties and self-confidence.

## 6.3 Climbing performance

### 6.3.1 Climb time

Differences in mean climb time (s) between the ability groups for the ascent styles top rope and lead are presented within Table 6.6. Mean  $\pm$  SD suggest that in all ability groups the lead ascent took longer than the top rope ascent. The time difference between ascent styles reduced as the ability groups increased. The largest difference between ascent styles was in the intermediate group.

**Table 6.6 Mean  $\pm$  SD climb time (s) for all ability groups and ascent styles.**

	Top rope (s)	Lead (s)	Lead vs top rope <i>t</i> -test
Intermediate* (18 Ewbank)	118 $\pm$ 16	183 $\pm$ 37	$t_{(10)} = 4.202, p = 0.006$
Advanced (22 Ewbank)	115 $\pm$ 20	164 $\pm$ 49	$t_{(10)} = 2.907, p = 0.09$
Elite (25 Ewbank)	136 $\pm$ 44	149 $\pm$ 37	$t_{(10)} = 1.833, p = 0.333$

\* A significant difference ( $p < 0.05$ ) between lead and top rope ascents within the ability group.

A two-way ANOVA revealed a non-significant interaction effect for ability group vs ascent style ( $F_{(2,43)} = 0.734, p = 0.487$ ) as well as for the main effect ability group ( $F_{(1,42)} = 0.646, p = 0.530$ ). However, there was a significant difference for the main effect ascent style suggesting that lead climbing took significantly longer than top rope climbing ( $F_{(1,43)} = 20.904, p < 0.0005$ ; the estimated variance explained by the mean effect was 34%). To determine where the differences between ascent styles lay, a series of independent sample *t*-tests were used within each ability group. Lead climbing took significantly more time than top rope climbing in the intermediate (mean difference = 65.29, CI = 99.9 – 30.67) but not the advanced (mean difference = 49.17, CI = 84.85 – 13.49) or the elite (mean difference = 31.49, CI = 72.31 – 9.34) groups.

### 6.3.2 Oxygen consumption and heart rate responses

Mean  $\pm$  SD in Table 6.7 suggests that the average HR and  $\dot{V}O_2$  responses of each group increased with increased levels of ability (lead and top rope combined). Furthermore, all ability groups exhibited a higher response during the lead compared to the top rope ascent.

**Table 6.7 Mean  $\pm$  SD oxygen uptake ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) and heart rate ( $\text{bts}\cdot\text{min}^{-1}$ ) in all ability groups and ascent styles.**

	Average $\dot{V}O_2$ ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ )	Average HR ( $\text{bts}\cdot\text{min}^{-1}$ )
Intermediate		
Top Rope	$30.12 \pm 3.33$	$155.52 \pm 7.3$
Lead	$32.43 \pm 2.36$	$158.92 \pm 18.32$
Combined	$30.55 \pm 2.79$	$156.94 \pm 12.42$
Advanced		
Top Rope	$32.12 \pm 2.21$	$159.13 \pm 11.62$
Lead	$34.03 \pm 3.77$	$169.96 \pm 12.19$
Combined	$32.13 \pm 3.03$	$164.26 \pm 12.83$
Elite		
Top Rope	$34.21 \pm 4.22$	$170.68 \pm 9.99$
Lead	$37.21 \pm 1.22$	$175.88 \pm 3.85$
Combined	$35.81 \pm 3.47^{***,**}$	$172.85 \pm 8.44^{***}$

\*\*The group is significantly different ( $p < 0.05$ ) from the advanced group

\*\*\*The group is significantly different ( $p < 0.05$ ) from the intermediate group

HR = heart rate,  $\dot{V}O_2$  = volume of oxygen

A two-way between groups MANOVA was performed to investigate ability group and ascent style differences in the combined dependent variables. As previously mentioned in section 6.2.2, MANOVA revealed a significant difference for the main effect ability group ( $F_{(8,58)} = 2.385$ ,  $p = 0.027$ ; Pillai's Trace 0.495), and the dependant variables were considered separately.

A one-way ANOVA revealed there was a significant difference between ability groups for the dependent variable average  $\dot{V}O_2$  ( $F_{(2,36)} = 6.343$ ,  $p = 0.015$ ; the estimated variance explained by the mean effect was 29%). Post-hoc LSD indicated that average  $\dot{V}O_2$  was significantly higher in the elite group compared to both the intermediate (mean difference = 5.26, CI 2.63 – 7.89) and advanced (mean difference = 3.67, CI 1.27 – 6.08) groups.



Furthermore, there was a significant difference between ability groups for average HR ( $F_{(2,36)} = 4.637$ ,  $p = 0.049$ ; the estimated variance explained by the mean effect was 23%). Post-hoc LSD indicated that average HR was significantly higher in the elite group compared to the intermediate group (mean difference = 15.63, CI 5.72 – 25.54), but unlike the average  $\dot{V}O_2$  response, this was not significantly higher than the advanced group (mean difference = 8.31, CI -0.68 – 17.3).

### 6.3.3 Blood lactate recovery

Data in Table 6.8 suggests that with the exception of the intermediate group, mean  $\pm$  SD BLa concentrations post-climb were similar between ability groups during both top rope and lead ascents. The intermediate lead group had a notably greater BLa concentration throughout the entire 15 minutes of recovery compared to all other ascent styles and ability groups. In the advanced and elite groups there was an initial decrease in BLa concentration (Table 6.8) which was evident between immediately post and five minutes post-climb. Interestingly, the intermediate lead and top rope groups had an increased BLa concentration between these time periods. After five minutes post-climb, the intermediate group mimicked a similar rate of decline as the advanced and elite groups. However, absolute BLa concentrations in both lead and top rope ascents remained higher in the intermediate compared to the advanced and elite groups throughout the entire recovery period.

**Table 6.8 Mean  $\pm$  SD blood lactate concentrations (mmol·L<sup>-1</sup>) during 15 minutes of passive recovery in all ability groups and ascent styles.**

		BLa 0 min post (mmol·L <sup>-1</sup> )	BLa 5 min post (mmol·L <sup>-1</sup> )	BLa 10 min post (mmol·L <sup>-1</sup> )	BLa 15 min post (mmol·L <sup>-1</sup> )
Intermediate	Top rope	5.23 $\pm$ 1	5.01 $\pm$ 0.9	4.31 $\pm$ 1.23	3.26 $\pm$ 1.1
	Lead	6.58 $\pm$ 2.7	6.64 $\pm$ 3.07	5.88 $\pm$ 2.69	5.02 $\pm$ 2.48
	Combined	6.1 $\pm$ 1.74	6 $\pm$ 1.99	5.25 $\pm$ 1.87 <sup>**,*</sup>	4.2 $\pm$ 1.88
Advanced	Top rope	4.78 $\pm$ 0.81	4.2 $\pm$ 1.14	3.49 $\pm$ 1.16	3.06 $\pm$ 1.02
	Lead	5.22 $\pm$ 1.12	4.48 $\pm$ 1.3	3.72 $\pm$ 1.19	2.94 $\pm$ 1.02
	Combined	4.99 $\pm$ 0.97	4.33 $\pm$ 1.19	3.6 $\pm$ 1.15	3 $\pm$ 0.99
Elite	Top rope	5.36 $\pm$ 1.39	4.79 $\pm$ 1.4	3.74 $\pm$ 1.19	3 $\pm$ 0.97
	Lead	5.5 $\pm$ 1.02	5.04 $\pm$ 1.3	3.96 $\pm$ 0.96	3.2 $\pm$ 0.69
	Combined	5.42 $\pm$ 1.2	4.89 $\pm$ 1.3	3.83 $\pm$ 1.1	3.1 $\pm$ 1.33

Post time periods represent the time from the end of the climb

\* The group is significantly different ( $p < 0.05$ ) from the elite group

\*\* The group is significantly different ( $p < 0.05$ ) from the advanced group

BLa = blood lactate

A two-way MANOVA was performed to investigate ability group and ascent style differences in BLA concentrations pre and post-ascents. Five dependent variables were used: BLA concentration pre, immediately post, and 5, 10 and 15 minutes post. The independent variables were ability group and ascent style. There was a non-significant interaction effect between ascent style and ability group on the combined dependent variables ( $F_{(8,64)} = 1.330, p = 0.245$ ; Pillai's Trace 0.285). Furthermore, there was a non-significant difference for the main effect ascent style ( $F_{(4,31)} = 1.665, p = 0.183$ ; Pillai's Trace 0.177). Unsurprisingly (given the mean data for the intermediate lead group presented within Table 6.8), there was a significant difference for the main effect ability group ( $F_{(8,64)} = 2.452, p = 0.022$ ; Pillai's Trace 0.469).

A three-way repeated measures ANOVA was used to describe the effects of ability group and ascent style on BLA responses immediately post and 5, 10 and 15 minutes post. As expected, there was a significant difference in BLA concentrations over time ( $F_{(4,136)} = 213.748, p < 0.0005$ , estimated variance = 86%). A series of post-hoc paired samples *t*-tests were used to assess differences in the combined BLA concentrations across the four time periods: immediately post and 5, 10 and 15 minutes post. Given the nature of the test and the behaviour of the BLA responses presented in Table 6.8, it makes sense that immediately post BLA concentrations were significantly higher than five minutes post ( $t_{(40)} = 5.089, p < 0.0005$ ), and immediately post was significantly higher than 10 ( $t_{(41)} = 10.921, p < 0.0005$ ) and 15 minutes ( $t_{(40)} = 20.035, p < 0.0005$ ) post recovery. Five minutes post BLA concentrations were also significantly higher than both 10 ( $t_{(40)} = 12.417, p < 0.0005$ ) and 15 ( $t_{(39)} = 18.034, p < 0.0005$ ) minutes. Furthermore, the 10 minutes post BLA concentrations were significantly higher than 15 minutes post ( $t_{(40)} = 11.541, p < 0.0005$ ).

There was also a significant difference for the interaction of BLA concentration (*combined* ascent styles) and ability group ( $F_{(8,136)} = 5.421, p < 0.0005$ , the estimated variance explained by the mean effects = 24%). To investigate the differences between ability groups at each time period, a series of one-way ANOVA's were used. It was revealed that at 10 minutes post, the intermediate group had a significantly higher BLA concentration than both the advanced (mean difference = 1.65, CI 0.61 – 2.68) and elite (mean difference = 1.41, CI 0.27 – 2.55) groups.

The three-way repeated measures ANOVA revealed there was a significant difference for the interaction of BLA concentration and ascent style ( $F_{(4,136)} = 3.036$ ,  $p = 0.020$ , the estimated variance explained by the mean effects = 8%). A series of independent  $t$ -tests were employed to determine which of the time periods the differences in BLA concentrations (between the top rope and lead) occurred. However, post-Bonferroni correction there was no significant differences.

The three-way repeated measures ANOVA also revealed a non-significant difference for the three-way interaction of BLA, ability group and ascent style ( $F_{(8,136)} = 1.427$ ,  $p = 0.191$ ) suggesting there were no differences in BLA concentrations between ascent styles within the each of the ability groups across the time periods.

#### **6.3.4 Delta cortisol concentrations (performance component)**

As previously mentioned, in order to depict the performance component of the cortisol response,  $\Delta$  values were calculated by subtracting the post 15 minute climb sample from the pre-climb sample. Mean  $\pm$  SD data in Table 6.9 suggest a higher performance cortisol response occurred during the lead compared to the top rope ascent in all ability groups. Furthermore, Table 6.9 suggests that there was an increase in performance cortisol concentration with the concurrent increase in climbing ability and physical difficulty of the route (i.e., top rope being more physically demanding than lead).

**Table 6.9 Mean  $\pm$  SD delta cortisol concentrations (performance component) in all ability groups and ascent styles.**

	Intermediate	Advanced	Elite
Top rope $\Delta$ cortisol (ng·mL)	0.83 $\pm$ 24.2	4.46 $\pm$ 31.51	31.28 $\pm$ 30.43
Lead $\Delta$ cortisol (ng·mL)	21.48 $\pm$ 35	29.68 $\pm$ 37.8	55.24 $\pm$ 21.76
<i>Combined <math>\Delta</math> cortisol (ng·mL)</i>	<i>8.34 <math>\pm</math> 28.77*</i>	<i>16.41 <math>\pm</math> 36.04*</i>	<i>41.26 <math>\pm</math> 28.8</i>

\* The group is significantly different ( $p < 0.05$ ) from the elite group

$\Delta$  = delta value

Although mean  $\pm$  SD data in Table 6.9 suggests there were differences between ascent styles and ability groups, a two-way ANOVA revealed a non-significant interaction (group vs ascent style) effect on the dependent variable ( $\Delta$  cortisol)

( $F_{(2,42)} = 0.018$ ,  $p = 0.982$ ).

However, there was a significant difference for the main effect ability group

( $F_{(2,43)} = 3.538$ ,  $p = 0.040$ ; the estimated variance explained by the mean effect was

14%). Post-hoc LSD revealed that the elite group had a significantly higher  $\Delta$  cortisol response than the intermediate (mean difference = 32.92, CI 1.1 – 64.74) and advanced (mean difference = 24.85, CI 1.53 – 48.18) groups.

There was also a significant difference for the main effect ascent style (*combined* ability groups) ( $F_{(2,43)} = 5.295$ ,  $p = 0.027$ ; the estimated variance explained by the mean effect was 11%) suggesting that the lead climb elicited a higher  $\Delta$  cortisol response than the top rope climb. However, when the groups were considered separately, a series of independent  $t$ -tests with Bonferroni correction revealed that there were no significant differences between ascent styles within any of the ability groups.

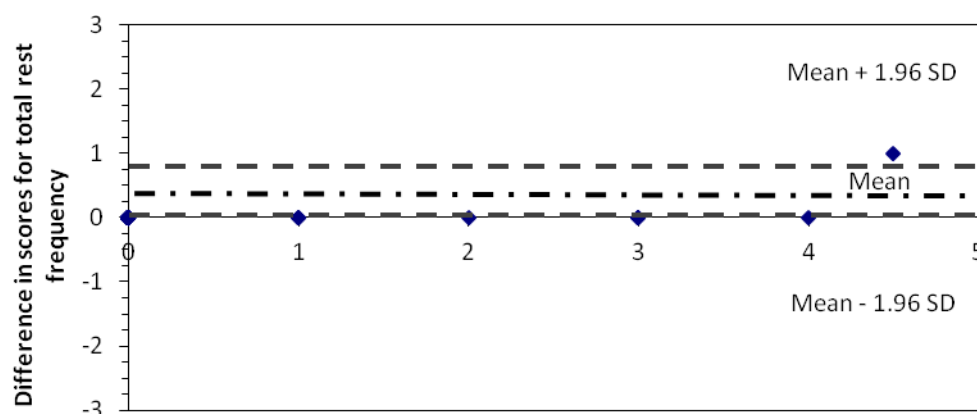
#### 6.4 Movement analysis

For the purpose of this study, video analysis was used to assess: *rest frequency*, *rest time* and *total static time* (defined in section 5.7) during the ascents of all participants. As previously mentioned, to ensure the results were not affected by the subjective nature of the interpretation, a professional rock climber who was not associated with the current study was asked to assess 20% of all videos (intermediate  $n = 3$ , advanced  $n = 4$  and elite  $n = 4$ ). In order to determine if there were potential differences in scores, a series of Bland and Altman (limit of agreement) plots were used to compare the findings of observer one and two. Mean  $\pm$  SD data is presented in Table 6.10. Both the researcher (observer one) and the independent climbing professional (observer two) had the same assessment criteria to measure: *rest frequency*, *rest time* and *total static time*. Bland and Altman plots (Figure 6.1) suggest high levels of agreement between observers for all of the variables assessed: *rest frequency* (A ( $R^2 = 0.97$ )), *rest time* (B ( $R^2 = 0.97$ )) and *static time* (C ( $R^2 = 0.99$ )). Almost all data points lie within 95% of the CI.

**Table 6.10 Mean  $\pm$  SD *rest frequency*, *rest time* and *static time* for observer one and two assessing movement patterns**

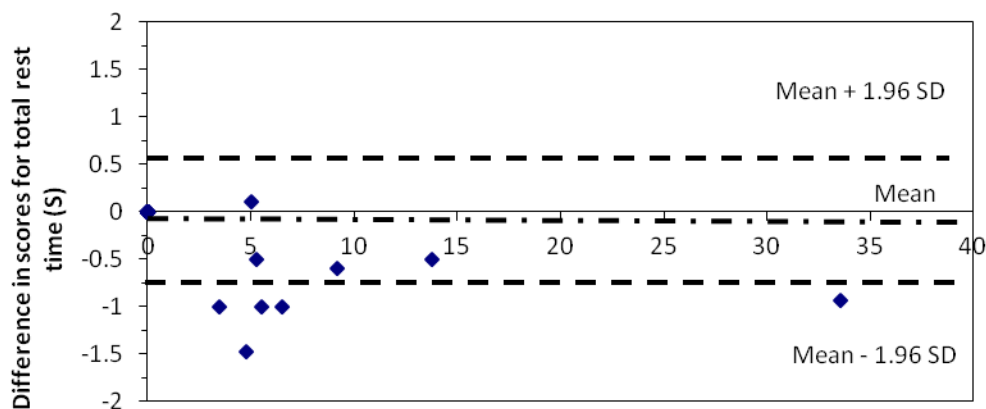
	Average rest frequency	Average rest time (s)	Average static time (s)
Observer one	2.1 $\pm$ 1.6	7.6 $\pm$ 9.3	46.7 $\pm$ 32.1
Observer two	2 $\pm$ 1.5	8.2 $\pm$ 9.4	46.7 $\pm$ 31.8

## Rest frequency



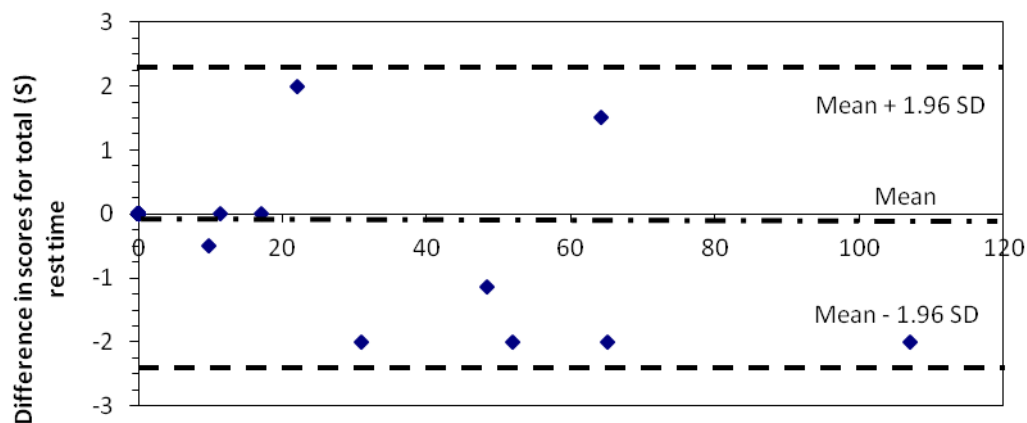
**A** Mean score for total rest frequency of observer 1 and 2

## Rest time



**B** Mean score for total rest time (s) for observer 1 and 2

## Static time



**C** Mean score for total static time (s) for observer 1 and 2

**Figure 6.1** Limits of agreement plots between observer's opinions of average *rest frequency*, average *rest time* and *static time* in intermediate (A), advanced (B) and elite (C) climbers during both top rope and lead ascents

#### 6.4.1 Movement time, between-group differences

Data within Table 6.11 suggests that intermediate climbers had a lower *rest frequency* compared to both the advanced and elite climbers. All three ability groups had a higher *rest frequency* during the lead compared to the top roped ascent. Furthermore, the *time (s) spent resting* increased with ability level. The *time (s) spent resting* was notably greater during the lead climbs in intermediate and advanced groups but not the elite group. The elite groups rested for a similar period of time during both top rope and lead ascents. The advanced group had the highest *static time*, this was notably lower in the intermediate group, and then lower again in elite group. *Static time* was considerably higher during lead compared to top rope ascents in both the intermediate and advanced groups, yet the elite group had a very similar *static time* for both ascent styles. The *percentage of static time which was spent actively resting* the hands and forearms was minimal for the intermediate climbers during both lead and top rope ascents, this percentage of time increased notably in advanced climbers and then even further in the elite climbers. All groups had a higher *percentage of static time which was spent resting* during a lead compared to a top roped ascent.

**Table 6.11 Mean  $\pm$  SD rest frequency, rest time, total static time and the percentage of static time spent resting for all ability groups and ascent styles.**

		Intermediate	Advanced	Elite
Average rest frequency <sup>+</sup>	TR	0.14 $\pm$ 0.38	3.6 $\pm$ 2.45	3.43 $\pm$ 2.21
	LD	1.4 $\pm$ 1.34	4.67 $\pm$ 2.24	7.2 $\pm$ 4.1
	Combined	0.67 $\pm$ 1.07 <sup>*,**</sup>	3.58 $\pm$ 2.52	5 $\pm$ 4.33
Average rest time (s) <sup>+</sup>	TR	0.71 $\pm$ 1.89	8.96 $\pm$ 5.76	15.47 $\pm$ 13.41
	LD	6.8 $\pm$ 6.96	15.15 $\pm$ 8.43	17.45 $\pm$ 13.21
	Combined	3.25 $\pm$ 6.92 <sup>*,**</sup>	11.9 $\pm$ 9.24	16.29 $\pm$ 17.38
Average static time (s) <sup>+</sup>	TR	31.43 $\pm$ 9.85 <sup>****</sup>	44.3 $\pm$ 9.96	24.68 $\pm$ 20.67
	LD	68.2 $\pm$ 21.7	72.4 $\pm$ 26.79	24.78 $\pm$ 19.31
	Combined	46.75 $\pm$ 24.14 <sup>*</sup>	57.74 $\pm$ 23.95 <sup>*</sup>	24.72 $\pm$ 22.88
Average percentage of static time spent resting <sup>+</sup>	TR	0.92 $\pm$ 6.3	21.56 $\pm$ 14.17	52.78 $\pm$ 25.15
	LD	4.99 $\pm$ 2.6	19.05 $\pm$ 8.27	72.84 $\pm$ 30.38
	Combined	6.16 $\pm$ 12.3 <sup>*,**</sup>	21.06 $\pm$ 15.11 <sup>*</sup>	63.37 $\pm$ 31.79

\*Shows the group is significantly different ( $p < 0.05$ ) from the elite group

\*\*Shows the group is significantly different ( $p < 0.05$ ) from the advanced group

\*\*\*Shows the group is significantly different ( $p < 0.05$ ) from the intermediate group

\*\*\*\*Shows a significant difference ( $p < 0.05$ ) between lead and top rope

<sup>+</sup> Shows data which has been log transformed pre-analysis

TR = top rope, LD = lead

After Log transformation a two-way between groups MANOVA was performed to investigate ability group and ascent style differences on the movement and rest times during all ascents. Four dependent variables were used: *Rest frequency*, *total rest time*, *total static time* and *percentage of static time which was spent resting*. The independent variables were ability group and ascent style. There was a significant interaction effect between ascent style and ability group on the combined dependent variables ( $F_{(8,70)} = 2.821, p = 0.009$ ; Pillai's Trace 0.488). There was also a significant difference for both the main effect ability group ( $F_{(8,70)} = 7.942, p < 0.0005$ ; Pillai's Trace 0.952) as well as the main effect ascent style ( $F_{(8,70)} = 9.697, p < 0.0005$ ; Pillai's Trace 0.533).

Although the two-way MANOVA revealed a significant difference for the interaction effect of group-by-ascent styles, when the dependent variables were considered separately ANOVA revealed there to be no-significant difference for *rest frequency* ( $F_{(2,43)} = 0.003, p = 0.997$ ), *total rest time* ( $F_{(2,43)} = 0.463, p = 0.633$ ), *total static time* ( $F_{(2,43)} = 0.619, p = 0.544$ ) or the *percentage of static time spent resting* ( $F_{(2,43)} = 0.681, p = 0.512$ ).

#### **6.4.2 Rest frequency**

For the main effect ability group, the dependent variables were considered separately (post log transformation). A one-way ANOVA revealed there was a significant difference between ability groups for the dependent variable *rest frequency* ( $F_{(2,43)} = 13.492, p = 0.008$ ; the estimated variance explained by the mean effect was 42%). Post-hoc LSD indicated that the elite group had a significantly higher number of rests compared to the intermediate (mean difference = 4.33, CI 1.95 – 6.72) but not the advanced (mean difference = 1.42, CI 0.73 – 3.57) group. Furthermore, the advanced group had a significantly higher number of rests compared to the intermediate (mean difference = 2.91, CI 0.76 – 5.06) group.

A one-way ANOVA suggested that there were significant differences in *rest frequency* between ascent styles (*combined* ability groups) ( $F_{(1,43)} = 7.900, p = 0.032$ ; the estimated variance explained by the mean effect was 16%). When the ability groups were considered separately a series of independent samples *t*-tests revealed that there were no significant differences between lead and top roped ascents.

#### **6.4.3 Total rest time**

A one-way ANOVA suggested there was a significant difference between ability groups for *rest time* ( $F_{(2,43)} = 8.494, p = 0.004$ ; the estimated variance explained by the mean effect was 32%). Post-hoc LSD revealed that the elite climbers rested more than the intermediate (mean difference = 13.04, CI 3.47 – 22.62) group. Furthermore, it was shown that the advanced group rested significantly more than the intermediate (mean difference = 8.65, CI 0.0012 – 17.29) group. A one-way ANOVA suggested that there was a non-significant difference in *total rest time* between ascent styles ( $F_{(1,43)} = 4.665, p = 0.148$ ).

#### **6.4.4 Total static time**

A one-way ANOVA suggested there was a significant difference between ability groups for *total static time* ( $F_{(2,43)} = 14.961, p < 0.0005$ ; the estimated variance explained by the mean effect was 45%). Post-hoc LSD indicated that the elite group had a significantly smaller *total static time* compared to the advanced (mean difference = 33.01, CI 50.69 – 15.34) and the intermediate (mean difference = 22, CI 41.5 – 2.46) group. Although not statistically significant, the advanced group had a smaller *total static time* than the intermediate (mean difference = 10.99, CI 6.69 – 28.66) group.

A one-way ANOVA suggested that there were significant differences in *total static time* between the two ascent styles ( $F_{(1,43)} = 7.563, p = 0.036$ ). Follow-up independent *t*-tests revealed that there was a significantly greater *total static time* in the intermediate ( $t_{(10)} = 4.470, p = 0.003$ ) group but not the advanced ( $t_{(10)} = 2.510, p = 0.66$ ) or elite ( $t_{(10)} = 0.504, p = 0.625$ ) groups.

#### **6.4.5 Percentage of static time which is spent resting**

A one-way ANOVA suggested there was a significant difference between ability groups for *percentage of total static time which is spent resting* ( $F_{(2,43)} = 20.495, p < 0.0005$ ; the estimated variance explained by the mean effect was 56%). Post-hoc LSD indicated that the *percentage of static time which was spent resting* was significantly greater in the elite compared to both the intermediate (mean difference = 57.21, CI, 40.26 – 74.16)



and advanced (mean difference = 42.30, CI, 26.99 – 57.61) groups. Furthermore, the advanced group spent a greater *percentage of static time resting* compared to the intermediate group (mean difference = 14.91, 0.4 – 30.22).

A one-way ANOVA suggested that there were no significant differences in *percentage of total static time which is spent resting* between the top rope and lead ascent styles ( $F_{(1,42)} = 7.563, p = 0.352$ ).

### Discussion for Study One

Previous research has studied the effects of on-sight lead and top rope climbing in intermediate rock climbers only (Draper et al., 2008; Draper et al., 2010; Hodgson et al., 2009). On-sight lead climbing appears to be the most stressful style of ascent in this ability group. However, there is little published data which has examined the mindset of higher ability climbers. Furthermore, there is no known research which has investigated the psychological and physiological interactions of higher ability rock climbers during an on-sight attempt on top rope or lead. Therefore, the purpose of study one was twofold: 1) to examine the psychological and physiological responses to difficult on-sight climbing with respect to ability level, and 2) examine the effects of ascent style (lead vs top rope) on the above responses. The main findings of the study were: 1) there were no differences in pre-climb anxieties between ascent styles ascents either between or within any of the ability groups, 2) with an increase in rock climbing ability there was an increase in both average  $\dot{V}O_2$  and HR, 3) with an increase in ability there was a concurrent increase in the physiological component of the cortisol response, and 4) isometric contraction may not represent up to one third of climb time as previously suggested. With an increase in ability level there appears to be a concurrent increase in the *percentage of static time which was spent resting* on a route.

To my knowledge, this is the first known study to investigate the physiological and psychological effects of on-sight top rope and lead climbing in different ability groups of rock climbers. In order to examine potential differences in multiple ability groups of rock climbers, the intermediate, advanced and elite groups were chosen from a pilot study (Appendix G) which defined homogenous grouping variables in rock climbers. As previously mentioned (section 5.1), this pilot study reviewed previous literature (Draper et al., 2009; Llewellyn & Sanchez, 2008; Michailov et al., 2009; Padrenosso et al., 2008; Watts et al., 1993b), and had communication with both scientific researchers, and climbing coaches (Priestley, 2010). The study concluded that: 1) there were five grade brackets that would fit climber's ability profiles appropriately, and 2) the Ewbank grading system or the Watts conversion should be used to conduct all statistical analysis.

In order to determine whether the use of self-reported grades were accurate, a further pilot study was conducted (Appendix G). Climbers were asked to report their best on-sight grade, and were then required to lead climb a competition style route (increasing in difficulty) under on-sight conditions. When these two grades were compared, it was found that males tended to over-estimate their ability by one grade (Ewbank), and females tended to under-estimate by one grade. For the current study, it was decided that the three ability groups would consist of rock climbers that had a best self-reported on-sight grade of Ewbank 17-18, 21-22 and 25+, these were defined as intermediate, advanced and elite groups respectively.

Fifty-eight participants were recruited, 20 intermediate, 23 advanced and 15 elite climbers. The distribution of participants which completed and fell during the on-sight ascent are presented within Table 6.1. On-sight climbing is defined as no prior knowledge or assessment of a route before it is attempted. All ascents were at the top of the ability group's respective grades, and therefore it is unsurprising that a combined total of 15 participants fell. Furthermore, if less climbers had fallen then the routes would have been set too easy for the required grade, and consequently participants would not have been ascending at or close to their maximum limit. The greater number of falls in the intermediate group (Table 6.1) may be attributed to a lack of regular training at the top of their ability (Table 5.1). Intermediate climbers may have been climbing for a significant amount of years, but do not always have a broad technical knowledge of the physical techniques used in climbing. Anecdotal evidence has suggested that it is a common attribute of intermediate climbers to ascend within their comfort zones, and they do not often push their climbing grade (Priestley, 2010). Consequently, these climbers have had a greater fall rate when asked to on-sight a route at or close to the top of their ability. Furthermore, Fuss and Niegler (2008) reported that lower level climbers apply a greater force than is necessary to grip the hold, which consequently leads to a rapid fatigue of the finger flexors. Although not measured within study one, over-recruitment may also in part explain the greater fall rate within the intermediate group. Over recruitment whilst gripping a hold would use unnecessary energy, potentially work the muscle more anaerobically, and therefore cause a build up of metabolites such as BLA within the muscle. Furthermore, this over recruitment would be reflected in a greater level of isometric contraction in the muscle, which is associated with decreased grip strength over time.

## **7.1 Anthropometric and demographic data**

The anthropometric and demographic characteristics of the climbers in study one are presented in Table 5.1. The participants making up the three ability groups were both homogenous, and comparable to previous rock climbing studies that assessed the groups of climbers individually: intermediate (Draper et al., 2008; Draper et al., 2010; Hodgson et al., 2009), advanced (Booth et al., 1999; Sheel, 2003) and elite (Bertuzzi et al., 2012; Billat et al., 1995; de Geus et al., 2006; Watts et al., 2000). Table 3.1 suggests that as climbing ability increased there was a significant ( $p < 0.05$ ) increase in the amount of climbing sessions attended per week. Furthermore, in agreement with previous research, the advanced and elite groups had a significantly ( $p < 0.05$ ) lower body fat percentage than intermediate climbers (Giles et al., 2006)

Body weight was significantly higher in the intermediate group only. These findings are not surprising, previous studies have reported a higher body weight in lower grade climbers when they were compared to their advanced and elite counterparts (Giles et al., 2006; Grant et al., 2003). Recent studies have shown that body fat percentage and weight may not be a prerequisite for a high level of bouldering performance, they may be just one of several attributes (Macdonald & Callender, 2011). Findings from study one suggest that both body fat percentage and total weight may be important for sport climbing where endurance and the repetition of lifting the body weight may be more frequent than during bouldering on short powerful routes. Furthermore, it has been suggested that strength-to-weight ratio is more important for roped climbing, and can better explain differences in ability levels (MacLeod et al., 2007; Philippe et al., 2011). Philippe et al. (2011) found that strength-to-weight ratio was closely correlated to best on-sight performance ( $R^2 = 0.946$ ,  $p < 0.001$ ). Unfortunately, neither maximal strength nor boulder to sport climbing ratio were assessed during study one.

## **7.2 Pre-climb**

Levels of anxiety have been reported in numerous sporting situations ((Jordet et al., 2006; Martens et al., 1990), including rock climbing (Draper et al., 2008; Draper et al., 2010; Hardy & Hutchinson, 2007; Hodgson et al., 2009; Sanchez et al., 2010a) 14-15 traditional, 19 sport, VS – E1 traditional and 7b+ - 8b French respectively)). However, little attention has been paid to the interaction of the psychological and physiological

aspects of pre-climb anxiety in different ability rock climbers. Those studies which have investigated pre-climb anxiety have only done so only in intermediate rock climbers ((Draper et al., 2008; Draper et al., 2010; Hodgson et al., 2009) 14-15 traditional, 19 sport and 3-4 years experience respectively). Study one was the first known investigation which attempted to determine any pre-climb psychological and physiological interactions, in three different ability groups ascending on top rope and lead.

Table 6.4 suggests there were minimal differences in pre-climb cognitive and somatic anxieties, as well as levels of self-confidence between the ability groups and ascent styles. These findings are similar to Hodgson et al. (2009) who also reported no significant differences in pre-climb anxiety between ascent styles (intermediate only). Table 6.4 suggests that somatic anxiety in study one decreased slightly with the increase in ability in both top rope and lead climbs, however cognitive anxiety had no trend. Self-confidence decreased with an increase in ability level, although these changes were minimal (Table 6.4), as was the effect size (12%). Draper et al. (2008) suggested that intermediate climbers had significantly higher levels of pre-climb anxiety during an on-sight lead climb compared to a second ascent. However, my study suggests that there may be no differences in pre-climb anxieties between on-sight top rope and lead ascents within any ability groups. Furthermore, a novel finding of my study is that there were no differences between ability groups when ascent styles were combined. Building upon the work of Draper et al. (2008) future studies should consider assessing pre-climb anxieties during multiple ascents in lower ability groups.

Previously, cortisol has been reported to be positively correlated with heightened CSAI-2R responses in intermediate rock climbers (Hodgson et al., 2009). However, as suggested in section 4.2 these correlations were very weak. Delta cortisol responses for the psychological component in study one are presented in Table 4.4. There were no trends and no significant differences either between ability groups or ascent styles. Findings from my study suggest there may be no differences in the psychological cortisol responses, adding to the suggestion that there may be no differences in pre-climb anxieties between ability groups or ascent styles within the study one.

Reinforcing the belief that there were no differences in pre-climb anxieties between groups or ascent styles in study one, Table 6.3 suggests there were no notable trends in

pre- $\dot{V}O_2$ . However, for pre-HR there appears to be an increasing trend in both lead and top rope conditions with the concurrent increase in ability level. Seeing as climbing experience (Table 5.1) was significantly greater in both the elite and advanced groups compared to the intermediate, it can be assumed that this increase in pre-climb HR was not a nervous response caused by elevated state anxiety traits. Tomaka, Blascovich, Kelsey, and Leitten (1993) showed that cardiac reactivity during a stress was positively associated with the appraisal of a challenge and negatively to a threat. Due to the level of experience within the advanced and elite groups, it could be assumed that they perceive the climb as a challenge and not as a threat, whereas as intermediate climbers may have seen it as more of a threat due to the lack of climbing at the top of their grade. Consequently, it may be possible that this increase in pre-HR seen in the advanced and elite groups is due to physiological readiness and not psychological nervousness. Further investigation into personality traits, perception, appraisal and toughness theory is warranted.

Elevated HR responses were traditionally related to an increase in sympathetic activation caused by an increase in anxiety in rock climbers (Draper et al., 2008; Williams et al., 1978). However, data in study one suggests that an increase in pre-climb HR may represent an elevated sympathetic activation caused by an athlete's physiological and psychological readiness. An increase in the sympathetic response has been suggested to occur as part of a behavioural response so the body can provide: a quick energy supply, re-distribution of blood and elevated HR (Carlson, 2010). Further adding to the belief that advanced and elite climbers may have a heightened sympathetic activation, it has previously been suggested that more advanced climbers have improved baroreceptor sensitivity (Sheel, 2004), which may in turn elevate HR pre-climb as part of an anticipatory response to exercise. In this case, the elite climber may be able to perform at an optimal level much quicker. Based on the data presented in Tables 4.2 and 4.3, this study supports the notion of being both physiologically and psychologically prepared pre-climb. However, since the increase in pre-climb HR was not significant, the conclusions made here are merely speculative ones. There remains a need to elucidate the underpinning variables in the highest calibre of climbers.

### **7.3 Climbing performance**

As shown within Figure 5.1, all the routes were 12.13m high and had sections which were both vertical and marginally overhung ( $\sim 110^\circ$ ). The time taken to ascend this distance was akin to previous studies which have conducted research on walls of similar heights and gradients (de Geus et al., 2006; Draper et al., 2008). Climb time was notably less than those studies which have reported on outdoor sport climbing routes, as well as maximal treadwall tests (Rosponi et al., 2012; Watts & Drobish, 1998).

There were no significant differences or notable trends in climb time between any of the ability groups whilst ascending on top rope. However, during the lead climb, as ability group increased, there was a reduced climb time (although SD's are large). Even though the route profiles and styles were evenly matched, the intermediate group took significantly longer to complete the route on lead compared to top rope, whereas the advanced and elite groups had no notable differences between their ascent styles.

Although no known study has assessed on-sight climbing in a variety of ability groups, it is known that for intermediate climbers, it takes significantly longer to ascend on lead compared to top rope. Table 5.1 suggests that the intermediate groups did significantly less training sessions per week compared to the advanced and elite groups. The significantly greater quantity of training in the advanced and elite groups could make for faster, and more efficient clipping positions whilst ascending on lead. Being able to clip both quickly and efficiently is particularly important as the longer this process takes the greater the time spent with only three points of contact on the wall (Hill, 2007).

#### **7.3.1 Motion analysis**

Climb time has been suggested to provide a good indicator of work duration (s). However, unlike many sports which have a continual work rate, climbing involves numerous rest periods, time spent shaking the hands and fingers, time spent in a static position and time spent inspecting the route ahead. Many climbers recognise the potential for taking opportune rests on easier sections of a climbing route, generally before a crux section is ascended, as shaking the hands has anecdotally been reported to aid in muscular recovery (Goddard & Neumann, 1994; Horst, 2008). Furthermore, active recovery post-climbing has been shown to significantly lower BLa compared to passive recovery (Draper et al., 2006a; Watts et al., 2000). However, it appears that

there is no known data which attempts to determine the amount of time that is spent conducting recovery/resting activities during a climb, and only one study quantified isometric time on a climb (Billat et al., 1995). Billat et al. (1995) suggested that isometric contraction, which was determined by the hips being in a stationary position, accounted for up to one third of total climb time. However, as previously mentioned (section 3.8.1) the hips not being in motion during an ascent does not mean that both the forearms are contracting isometrically. The numerous resting and shaking out periods seen on a sport climb are generally conducted during this static time or time in which the hips would not be moving. Study one was the first known investigation which attempted to determine the amount of *rest* and *static time*, and more importantly *the percentage of this static time which is spent actively resting* out the fingers and forearm muscles.

Although it was found that the advanced and elite groups had similar climb times for both lead and top rope climbing, a further interesting finding was that the elite group had a similar amount of time spent in a *static position* during both ascent styles, even though the lead ascent required clipping on route. Whereas the intermediate (mean difference = 36.77s) and advanced (mean difference = 9.46s) groups spent a significantly longer period in a *static position* during the lead climb compared to the top rope. However, as shown in Table 6.11, out of the time spent in a static position, the *percentage of time which was spent resting* the fingers and forearms significantly increased with the concurrent increase in ability group. Furthermore, the estimated variance between groups explained by the *percentage of static time which is resting* was 56%. Further statistical analysis revealed that the elite group spent significantly more time resting during static time than both the intermediate (mean difference = 57%) and advanced (mean difference = 42%) groups. Although no known study has directly assessed the effectiveness of taking rests on a route, there is much anecdotal evidence which suggests that resting on a route at appropriate places makes a climber feel less pumped and promotes recovery (Goddard & Neumann, 1994; Horst, 2008). Furthermore, MacLeod et al. (2007) and Philippe et al. (2011) found that intermittent contractions on a climbing specific test significantly improved time-to-failure in advanced and World Cup level climbers. The authors found that compared to a control group, climbers had a significantly greater re-oxygenation during the rest periods which accounted for 41.1% of the variability in the force time integral (FTI defined as  $N \times S$ ).



However, no known rest data currently exists for the re-oxygenation differences amongst different ability groups of rock climbers.

Data in Table 6.11 suggests that the current belief that one third of climb time is spent in isometric contraction, may not be true for all ability rock climbers. More importantly, not only does static time significantly change with different ability groups, but the rests that occur during these periods also appear to be significantly different. Therefore, the use of solely static time as a marker of time spent in isometric contraction is almost meaningless in a sport climbing context. Future studies should make note of the *percentage of static time which is spent resting* on a route, as well as the *rest frequency* and *total static time*. Although no motion task analysis was conducted, it was clear during the on-sight ascent advanced and elite climbers would often rest out their hands *whilst* inspecting the moves ahead, pre-planning the remainder of the route. Overall, the rest data reported in Table 6.11 suggests that based on a climbers level of experience and best on-sight grade (Table 5.1), the greater the climbing ability, the more mechanically efficient they may be on a route, resting significantly more compared to the intermediate group. Furthermore, it was observed that this time was not only spent resting, but was combined with inspecting the moves ahead, something which was not seen in the intermediate group. This is in agreement with previous studies (Fuss & Niegl, 2008; MacLeod et al., 2007) which suggested that the more experienced a climber is, the more they read a route, assesses the correct manner in which to grip handholds, and importantly, where they may be able to take opportune rests during the ascent.

It is possible that the above named differences in the climbing styles may have had an effect on a climber's physiological function. Increased rest periods may have reduced the degree of hyperaemia, and aided the transportation and distribution of blood metabolites to other places within the body for utilisation. For example, non-exercising muscle has been shown to use lactic acid which has been produced elsewhere in the body (Jorfeldt, 1970; Oyono-Enguelle et al., 2008), and muscle re-oxygenation has been shown to increase in non-exercising forearms muscles both during (Ogata, Akai, & Nakazawa, 2008) and after (Nagasawa, 2008) knee extension. Furthermore, HR has been shown to increase during prolonged isometric exercise without a concurrent increase in  $\dot{V}O_2$  (Cornett et al., 2000; O'Leary, 1993; West et al., 1995). Heart rate has also been shown to elevate upon release of intermittent forearm contractions in non-

climbers (at 60% of MVC) (Cornett et al., 2000). All of these factors may potentially affect the climb average  $\dot{V}O_2$  and HR responses throughout a route.

It is clear that resting on route may have had different effects on the physiological responses in the three ability groups in study one. However, it is currently unclear what these changes might be, and which mechanisms are most affected. Furthermore, it is not known what adaptations there are in the forearm flexors of multiple ability groups of climbers. A greater investigation of HR and BF, as well as  $O_2$  kinetics within the forearm flexors would provide a clearer understanding of what the responses are, and what differences may occur between ability groups during rests on a climbing route and more importantly, are they beneficial to performance?

### **7.3.2 *Oxygen consumption and heart rate responses***

To date previous psychophysiological studies have focused solely on intermediate ability rock climbers (Draper et al., 2008; Draper et al., 2010; Hodgson et al., 2009). These studies have reported low  $O_2$  uptake during (Table 3.4) top rope and lead climbing (Draper et al., 2010), as well as on-sight climbing (Draper et al., 2008). There are no known studies which have assessed the physiological and psychological profiles of advanced or elite climbers, ascending on routes near the top of their respective ability levels. As previously mentioned (section 6.3.2) the  $\dot{V}O_2$  and HR responses in study one were averaged during the climbs (Table 6.7). No known study has compared multiple ability groups during on-sight rock climbing. Both the  $\dot{V}O_2$  and HR responses were similar to previous studies which have investigated the physiological responses in intermediate climbers (Watts & Drobish, 1998) and *some* elite (de Geus et al., 2006) climbers, when ascending near the top of their respective ability level. However, the  $\dot{V}O_2$  responses in Table 6.7 are notably higher compared to previous studies which have investigated physiological responses of *some* advanced (Billat et al., 1995) and elite (Sheel, 2003; Watts et al., 2000) climbers. However, it should be noted that in these previous studies, the advanced and elite climbers were performing either well below their best on-sight grade, or on a pre-practiced route which was also of a lower grade. Previously ascending below your best performance grade has been shown to elicit a lower  $\dot{V}O_2$  and HR response (Mermier et al., 1997; Sheel, 2003).

Study one is the first known investigation to show that  $\dot{V}O_2$  and HR increased both with ability group and ascent style difficulty (lead climbing being physically more demanding than top rope). Table 6.7 suggests both an increasing trend in  $\dot{V}O_2$  and HR with ability group. The elite group had a significantly greater average  $\dot{V}O_2$  than both the intermediate and advanced groups. A similar response was seen for average HR, except only the elite climbers had a significantly higher HR than the intermediate group.

An elevated HR over the respective  $\dot{V}O_2$  was traditionally put down to an increase in the nervous response in rock climbers (Billat et al., 1995; Draper et al., 2010; Giles et al., 2006; Williams et al., 1978). However, this study has broken down pre and post-climb components, and has shown that the previously suggested elevated anxiety response may not be true. Table 4.6 suggests that HR increases with a concurrent increase in ability and route difficulty. Elite and advanced rock climbers who train on a regular basis, and have been lead climbing for a notable number of years (Table 5.1) are not likely to feel a nervous response (fear of falling) during indoor rock climbing on a wall which was 12.13m high, whether on lead or top rope. Although white coat syndrome cannot be ruled out, it would be unlikely that it would cause HR to be elevated further with an increase in the ability level of the climber. The greater physical difficulty of the routes is more likely to be a cause of the significant increase in both HR and  $\dot{V}O_2$  seen in the elite group. Previously, an increase in work load has been shown to increase the HR and  $\dot{V}O_2$  responses in rock climbers (Watts & Drobish, 1998). Furthermore, a recent study showed that with an increase in rock climbing speed there is an increase in the HR and  $\dot{V}O_2$  responses (Rosponi et al., 2012). Study one found that during lead climbing, total ascent time was reduced as ability increased, even though more time was spent resting, and so the overall speed of the actual climbing must have been faster. This may in part explain the significantly heightened  $\dot{V}O_2$  and HR responses seen in the advanced and elite groups. Furthermore, since all routes in study one were on the same section of wall, the increase in difficulty of the routes was caused by fewer holds and holds which were more difficult to grip, i.e. more sloping or with smaller edges as well as bring off-set (anterior-posterior). Both these variables have previously been shown to significantly increase the requirement of a more forceful handgrip strength (contact force N) to stay on the hold (Amca et al., 2012).

### 7.3.3 Aerobic – anaerobic contributions

Preliminary studies investigating rock climbing suggested that the sport had little reliance on aerobic metabolism (Billat et al., 1995). However, over the last 10 years studies have attempted to gain a greater understanding of the energy systems involved in different disciplines of climbing (Bertuzzi et al., 2007; de Geus et al., 2006; España-Romero et al., 2012; Pires et al., 2011b; Rodio et al., 2008). Although data remains discordant, recently there is evidence to suggest that the belief that the aerobic metabolism does not play a major role in climbing maybe untrue (Pires et al., 2011b; Rodio et al., 2008; Sheel, 2003). Bertuzzi et al. (2007) suggested that the increased aerobic contribution seen during their study probably occurred to meet the energy demand imposed by taking rests on the route to shake out and chalk up the hands.

Findings from our study suggest that this may be true, as not only did  $\dot{V}O_2$  significantly increase with ability group, whilst BLa was significantly decreased (post-10 min) (Table 6.8), but, as seen in Table 6.11, the *rest frequency* and *percentage of static time spent resting* were significantly greater in the advanced and elite compared to the intermediate groups. Interestingly, the post-climb BLa (Table 6.8) concentrations suggest that in the intermediate group, at least some of the additional energy demand may be met through an increased relative contribution by anaerobic glycolysis, as BLa was significantly higher (post-10 min) than both the advanced and elite groups. Furthermore, this contribution may decrease in more experienced groups, as BLa was significantly lower post-10 minutes, and mean  $\pm$  SD data in Table 6.8 suggest it remained notably lower throughout the entire 15 minutes of recovery.

Findings of the current study have made a significant contribution to the belief that, although sport climbing is often short in duration, between 90s – 300s (de Geus et al., 2006; Draper et al., 2008; Sheel, 2003), there may be a larger aerobic contribution than previously thought. A novel finding of this study is that not only may there be a larger activation of the aerobic metabolism, but it appears to further increase with the concurrent increase in ability level and route difficulty (top rope vs lead). Furthermore, this may be affected by the rest frequency and rest duration on a route.

### **7.3.4 Blood lactate responses**

It has been well documented that rock climbing elicits a small BLa response compared to running and cycle ergometry, predominantly due to the reliance on the small muscle mass in the forearm flexors (Giles et al., 2006). As previously mentioned it is difficult to compare climbing data from and between previous studies, due to the variety of protocols used. One physiological response has become clear, post-climbing there is a significant decrease in BLa over time (as suggested within Table 6.8) even during passive recovery. Previous studies investigating on-sight climbing in intermediate climbers, have reported comparatively low BLa concentrations ( $2.5 - 3.7 \text{ mmol}\cdot\text{L}^{-1}$ ) post-climb (Draper et al., 2008; Draper et al., 2010).

Draper et al. (2008) found that in intermediate climbers, post-climb BLa concentration was significantly higher during an on-sight lead compared to a second lead. After 15 minutes of passive recovery, BLa concentrations for all ascents had returned to those seen pre-climb. The authors suggested that the significantly higher BLa concentration seen immediately-post on-sight climb was due to significantly elevated pre-climb cognitive and somatic anxieties, and an increase in climb time. Findings from study one agree in part with the finding of Draper et al. (2008). The current study also found that intermediate climbers elicited a significantly higher BLa concentration (post-10 min) after the on-sight climb compared to all other groups (as shown in Table 6.8).

Furthermore, BLa for the intermediate on-sight lead climb was notably higher (but not significant) than all other groups and ascent styles throughout the entirety of recovery. Climb time was also significantly greater during the lead compared to top rope ascents (Table 6.6), suggesting that the longer climb time may have contributed to the increase in BLa concentration seen after the lead ascent. However, Table 6.4 shows no significant differences in any anxieties between ascent styles or ability groups, and no trends or significant differences in pre-climb  $\Delta$  cortisol. Consequently, the increase in BLa is more likely due to the significantly longer climb time in the lead compared to the top rope ascent, and not an increase in anxiety as previously suggested (Draper et al., 2008). This may have been further exacerbated by the lack of rest periods seen within the intermediate groups, and consequently a greater time may have been spent in isometric contraction.

Sheel (2004) suggested that it seems reasonable to conclude that with an increase in climbing difficulty there is an increase in BLa. Data from study one suggests that this

may not be true when different ability climbers are performing at the top of their respective ability levels; i.e. working at the same respective intensity. Blood lactate concentrations in the advanced and elite groups were similar both between the two groups and the ascent styles, these were notably lower than all values seen in the intermediate group, and significantly lower at post-10 minutes (Table 6.8). It would appear that the lower level climbers have an elevated BLa response to lead climbing compared to top rope due to an increased climb time. This lowered BLa response in the advanced and elite climbers may be due to several factors: a greater contribution of aerobic glycolysis, given the duration of climb times (Table 6.6), a more efficient grip on holds creating a lower co-efficient of friction (Fuss & Niegl, 2008), a greater BLa uptake in non-exercising muscle (Oyono-Enguelle et al., 2008) or a decrease in muscular hyperaemia due to significantly greater rest periods (Table 6.11).

Billat et al. (1995) suggested that up to one third of climb time was spent in isometric contraction. As previously mentioned findings from study one suggest that this may not be the case (section 3.8.1) in all ability level climbers. Furthermore, the links presented by Billat et al. (1995) between static time and isometric contraction seem unfounded. Table 6.11 suggests that average *static time* was significantly greater in intermediate and advanced groups compared to the elite group, and that the estimated variance explained by *rest frequency* was 42%. Rest frequency was significantly higher in both the advanced (mean difference 2.91, CI 0.76 – 5.06) and elite (mean difference CI 4.33, CI 1.95 – 6.72) groups compared to the intermediate, and the estimated variance explained by the *percentage of static time spent resting* was 56%. Furthermore, with large mean differences and CI's between groups, it seems probable that this increased rest period and time spent shaking the hands may explain some differences in BLa concentrations. Particularly as both the advanced and elite groups had significantly lower BLa concentrations (10 minutes post) than the intermediate group.

For the intermediate group, the continual isometric contraction with little vertical movement up the wall may be a cause of the elevated BLa concentration. Lesser ability climbers have previously been suggested to over recruit muscle fibres on holds during ascents compared to climbers with higher ability levels (Fuss & Niegl, 2008; Goddard & Neumann, 1994; Horst, 2008). As previously mentioned, Fuss and Niegl (2008) investigated climbers during a competition and suggested that the better the climber, the smaller the contact force, the shorter the contact time, the smaller the impulse and the

better the smoothness factor, and the higher the coefficient of friction. The authors suggested that beginner climbers will apply a greater force than is necessary to a grip, which consequently leads to a rapid fatigue of the finger flexors. Data from study one (Table 6.8) suggests that elevated BLa concentrations, which may be caused by over gripping, could be exacerbated by the need for clipping during the climb.

#### **7.4 Conclusion**

The increase in pre-climb HR has traditionally been associated with elevated levels of anxiety. However, data from study one suggests that HR increased with the concurrent increase in ability group, and this was further matched with decreases in pre-climb anxieties and no trends or significant differences in  $\Delta$  cortisol. Therefore, the elevated pre-climb HR may reflect an increased physiological and psychological readiness and might not be a reflection of an elevated nervous response.

Whilst on-sight climbing, the intermediate climbers took longer to ascend on lead than top rope. Elite and advanced climbers appear to have the same climb times regardless of ascent style, suggesting they are physically more efficient on route. Furthermore, the resting actions which take place on a route appear to differ greatly between ability groups. The greater the ability of the climber, the more they appear to rest on a route. However, the *percentage of static time which is spent resting* on a route is vastly greater in elite and advanced climbers. It is possible that these rest periods which are used for shaking the fingers and hands may have an effect on BLa concentrations, as well as HR responses, and  $O_2$  uptake during an on-sight climb. However, the definitive existence or extent to which resting on a route affects these physiological responses in multiple ability groups of climber's remains unclear.

For the first time, BLa,  $\dot{V}O_2$ , and HR responses have been assessed in three ability groups performing at, or close to the top of their respective best on-sight grades on top rope and lead. The significantly higher  $\dot{V}O_2$  and HR responses, as well as the significantly lower BLa concentrations seen in the advanced and elite groups (post-10 min) adds notable evidence to the emerging belief that rock climbing uses a greater aerobic contribution than first thought. Furthermore, this study suggests that not only may there be a greater aerobic contribution than previously first thought, but it appears

to further increase with rock climbing ability and route difficulty. However, the specific energy system contribution within the musculature of the forearm flexors still remains unclear. The effects of intermittent contractions, as seen during rest periods in climbers, may well have caused some differences in aerobic/anaerobic concentrations, HR and  $\dot{V}O_2$  responses. A further investigation into the  $O_2$  kinetics and BF responses within the forearm flexors of a range of different ability rock climbers may help to highlight potential differences in muscle energetic, and energy system contributions. Such investigation would also quantify the capacity to re-oxygenate both during intermittent contractions, as well as during post-climb recovery. The following chapter 'Introduction to Study Two' reviews the limited previous research into the forearm flexors of rock climbers, with a particular focus on haemodynamics, including muscle re-oxygenation and BF responses to sustained and intermittent contractions.



### Introduction to Study Two

As can be seen in Chapter 6, when different ability rock climbers were asked to on-sight a route at the top of their ability, there appeared to be minimal differences in anxieties and self-confidence. Somatic anxiety was the only psychological component measured which showed a slight decrease with the concurrent increase in ability group, but no significant differences or meaningful effects were observed. However, there did appear to be some changes and trends in physiological function between the ability groups during both lead and top rope ascents. There were significant differences in both average  $\dot{V}O_2$  and HR between ability groups, but not ascent styles. Combined (lead and top rope) average  $\dot{V}O_2$  was significantly higher in elite compared to intermediate and advanced climbers, and average combined HR was significantly higher in elite compared to intermediate climbers. Average  $\dot{V}O_2$  rose with both the increase in ability group, and the increase in ascent style difficulty (i.e. lead climbing is physically more demanding than top rope climbing). Heart rate responses had the same pattern, albeit the differences were slightly larger than those seen in  $\dot{V}O_2$ .

Table 6.8 suggests that the BLa recovery profiles were different between groups. The BLa concentrations in both the advanced and elite climbers on lead and top rope decreased from immediately post, through to 15 minutes post. However, BLa concentrations in the intermediate group continued to increase until 5 minutes post, it then followed the same rate of decline as the other groups, although absolute values remained higher. Furthermore, BLa concentrations post-lead climb in the intermediate group were notably higher than all other ability groups and ascent styles, and significantly higher 10 minutes post-climb. The performance aspect of the  $\Delta$  cortisol response revealed that concentrations increased as both ability group and ascent style difficulty increased. The elite group had a significantly higher  $\Delta$  cortisol than all other groups (Table 6.9), suggesting a greater physiological demand was placed on the body. Video analysis revealed that there were significant differences between ability groups for the resting periods during the on-sight climbs. *Rest frequency*, *rest time* and the *percentage of static time which was spent resting*, all significantly increased with the concurrent increase in ability group.

The initial hypothesis for this study was that there may be a greater nervous response to on-sight climbing in intermediate rock climbers compared to the advanced and elite climber, and that this response may be further exacerbated by lead climbing. It was also thought that there may be a greater nervous response during lead compared to top rope climbing within the intermediate group and potentially advanced groups. Furthermore, it was expected that elite climbers may have a greater mechanical and physiological efficiency resulting in a reduction of some physiological responses. However, the initial study revealed the opposite; no meaningful differences were observed for the psychological components, and there were increases in physiological responses with increased ability and ascent style difficulty. Therefore, a closer investigation into the physiological responses of rock climbing in different ability groups is warranted. Particularly a study which investigates potential ability group differences in the haemodynamic responses of rock climbers, as the elite climbers currently appear to rest on-route significantly more than the other groups.

### **8.1 Forearm flexors**

One area which is of particular interest to rock climbers and exercise physiologists is the responses of the forearm flexors. It has been suggested that the forearm flexors may be one of the most important trainable aspects with regards to increasing a climber's performance (Goddard & Neumann, 1994; Horst, 2008; López-Rivera & González-Badillo, 2012; Schweizer et al., 2007). Previous research into grip strength and forearm flexors in rock climbers is described section 3.6. Although much investigation has gone on into grip strength, little attention has been paid to the haemodynamic responses of the forearm flexors during sport specific contractions. There are only three known studies which have researched the topic; two focused on tissue oxygenation using near infrared spectroscopy (NIRS) (MacLeod et al., 2007; Philippe et al., 2011) and one assessed post-contraction BF (Ferguson & Brown, 1997). Ferguson and Brown (1997) were the first and only known authors to assess BF in rock climbers. The study looked at arterial blood pressure and forearm vascular conductance responses to both sustained and intermittent contractions, as well as arterial occlusion (induced tourniquet ischemia) in sedentary subjects and elite sport climbers (top 10% of graded difficulty).

Participants were laid in a supine position and asked to pull on a handgrip strain gauge at 40% of MVC until exhaustion occurred. Blood flow was measured at rest and post 5s

and 15s, followed by 15s samples for two minutes of recovery. The authors reported no differences between groups in MVC or time-to-failure during the sustained contraction. However, for the intermittent contraction the climb group took significantly longer to fatigue. Post-sustained contraction, BF peaked in the climb and sedentary groups at 44.1 (3.1) and 28 (2.4)  $\text{mL} \cdot \text{min}^{-1} \cdot 100\text{mL}^{-1}$  respectively. Vascular conductance increased fourfold in the sedentary group and 7.5-fold in the climbing group. Vascular conductance remained higher in the climb groups for the whole of the two minute recovery period. After the intermittent contraction, BF was significantly greater in the climb group ranging from 38.7 to 48.9  $\text{mL} \cdot \text{min}^{-1} \cdot 100\text{mL}^{-1}$  compared to 24.3 to 28.6  $\text{mL} \cdot \text{min}^{-1} \cdot 100\text{mL}^{-1}$  in the sedentary group. During the intermittent, contractions vascular conductance varied considerably, it was suggested this was due to problems arising from keeping the forearm still during the brief rest periods. While BF has been studied extensively in other more mainstream sports, it has received almost no attention in rock climbing, likely due to the difficult nature of assessment in rock climbing, and the apparatus and skill required to perform vascular measurements.

## **8.2 Blood flow**

Measuring BF requires an experienced sonographer who is extensively trained in ultrasound. The nature of the measurements often requires the participants to remain extremely still. For this reason, many assessments of sporting performances are not done in their natural setting but in a laboratory, where external variables affecting BF can be controlled for. Previous studies have sought to examine exercise induced vascular adaptations in athletes from a variety of different sports (Green, Spence, Rowley, Thijssen, & Naylor, 2012; Huonker, Schmid, Schmidt-Trucksäb, Grathwohl, & Keul, 2003; Wijnen et al., 1991).

The majority of previous research has examined the adaptations that occur to the vessel diameter, BF, velocity, and endothelial function of conduit and elastic arteries in athletes (Abergel et al., 1998; Green et al., 2012; Huonker et al., 2003; Karagounis, Maridaki, Papaharalampous, Prionas, & Baltopoulos, 2009; Petersen et al., 2006; Rowley et al., 2012). Studies have suggested that intense training leads to an increase in the diameter of the conduit vessels, resulting in an improved functionality. In cycling, training has shown to lead to an increase in the diameter of the carotid artery (Abergel et

al., 1998), and the femoral artery (Kool, Struijker-Boudier, Wijnen, Hoeks, & van Bortel, 1992). Judo athletes have been shown to have significantly enlarged brachial and radial arteries, and a significantly higher BF through the ulnar and popliteal arteries (Karagounis et al., 2009). Gaining knowledge of the changes in vessels, and why they occur is an important part of being able to understand and improve performance in sporting individuals. To date this has not been done with rock climbers.

It is possible that these regular episodic increases in BF and the associated shear stress, which is related to systematic exercise training may cause the exercise induced vessel enlargement frequently seen in trained and elite athletes. Prior, Yang, and Terjung (2004) suggested that the sustained increases in BF through the arteries supplying the exercising muscles with blood, plays a major role in the regulation of lumen diameter of the vessel involved. Karagounis et al. (2009) suggested that changes in vascular structure are triggered by the enlarged volumetric BF and subsequent endothelial shear stress, brought on by physical training. It is the belief that the structural enlargement of conduit vessels is dependent on the shear stress mediated release of nitric oxide (NO) (Prior, Lloyd, Yang, & Terjung, 2003; Stoner et al., 2012), and that this may be an adaptive response to mitigate in increased wall stress brought on by repeated muscle contractions seen during exercise (Karagounis et al., 2009; Prior et al., 2003; Tuttle et al., 2001). Nitric oxide has been shown to be released from the endothelium when BF through the conduit artery is increased (Green, Maiorana, O'Driscoll, & Taylor, 2004a; Green et al., 2004b; Maiorana, O'Driscoll, Taylor, & Green, 2003). It appears that regular training causes an increase in the expression of endothelium constitutive nitric oxide synthase (eNOS), resulting in a chronic adaptation of the NO vasodilator system (Maiorana et al., 2003).

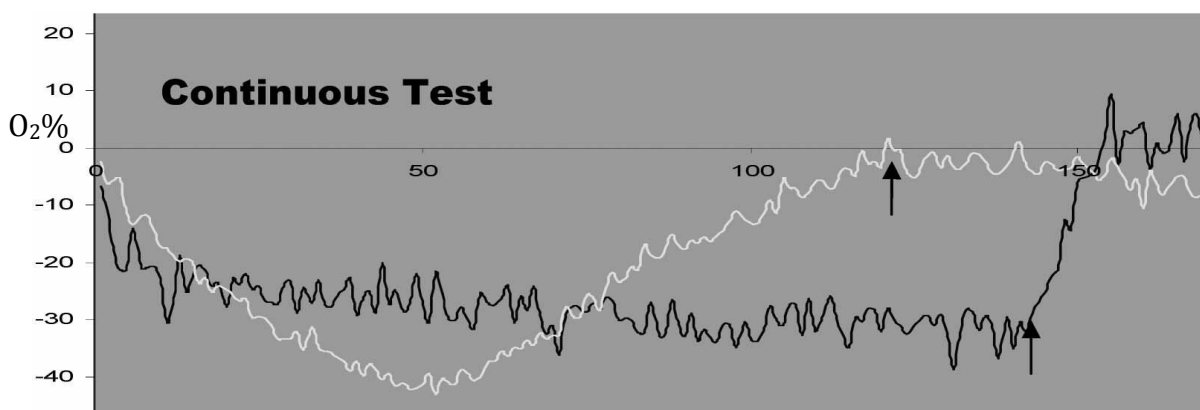
### **8.3 Near infrared spectroscopy**

Two known studies have used NIRS to investigate O<sub>2</sub> saturation kinetics in rock climbers, during both intermittent and sustained contractions (MacLeod et al., 2007; Philippe et al., 2011). MacLeod et al. (2007) were the first authors to use NIRS to assess forearm responses to a climbing specific task in intermediate climbers and non-climbers. Figure 3.4 shows the test apparatus developed to assess changes in muscle blood volume and oxygenation in the FDS. The apparatus consisted of a force plate which allowed the distal parts of the fingertips to overlap, creating a similar open crimp

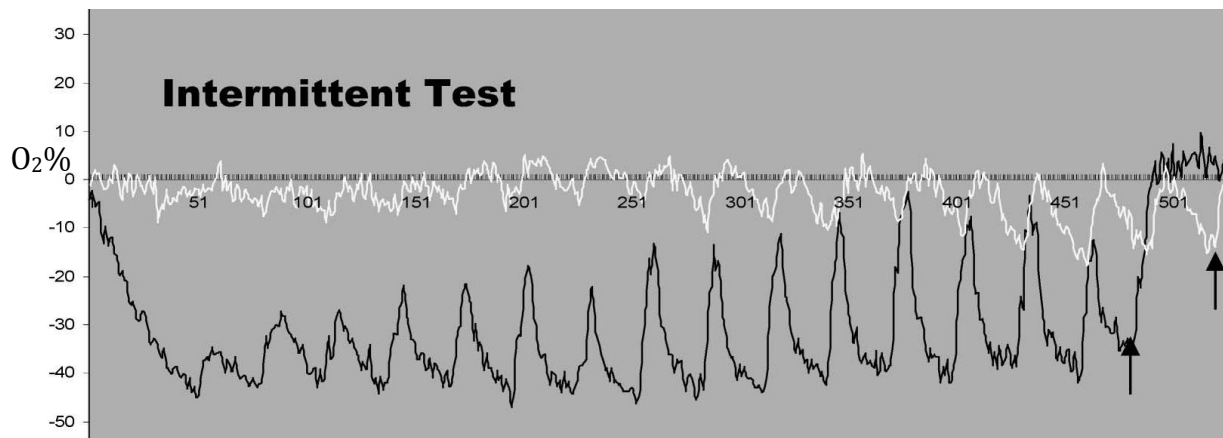
grip to that seen in rock climbing. MacLeod et al. (2007) reported a significant relationship between MVC and climbing grade performance. Moreover, MVC explained 49.9% of the variability of the climbing grade. Group mean endurance times were similar for both the sustained and intermittent contractions. However, the FTI, was significantly greater for intermediate climbers compared to non-climbers during the intermittent test. During the sustained contraction, group mean change in muscle blood volume and oxy-haemoglobin ( $\text{HbO}_2$ ) was assessed at 20% intervals between the start and the end of the test. Figure 8.1 presents the  $\text{O}_2$  saturation profiles for climbers and non-climbers during a sustained contraction. Oxygen saturation decreased in non-climbers at the start of the contraction, but before the exhaustion occurred, the FDS began re-oxygenating. In the climbing group, the FDS de-oxygenated and then remained at a low level until exhaustion. For the intermittent test, de-oxygenation occurred during the contraction phase and then re-oxygenated during the rest phase, creating a series of peaks and troughs (Figure 8.2). Due to the differences in contraction times, three rest phases were averaged for the first, middle and last phases of contractions. Climbers had significantly greater rest phase re-oxygenation during the middle and last three contractions. Furthermore, there was a significant relationship between rest phase re-oxygenation and the FTI. The authors concluded that muscle re-oxygenation during the rest phases was an important determinant to climbing specific finger endurance. The authors suggested re-oxygenation was not dependent on the pressor response during a climbing endurance test, due to the lack of relationship between rest phase re-oxygenation and the magnitude of the pressor response itself.

The study conducted by MacLeod et al. (2007) were the first to investigate muscle oxygenation (using NIRS), one of the haemodynamic parameters associated with sport specific hand grip strength. This opened up several avenues of future research into the determinants of sport specific grip strength. The study revealed differences in de-oxygenation and re-oxygenation of the FDS between climbers and non-climbers. Although MacLeod et al. (2007) made great contributions to furthering the knowledge of what occurs in the forearm flexors during climbing, Philippe et al. (2011) suggested that muscle choice in the study was not ideal for the sport, and rather the FDP was considered more important as it bends the last joint of fingers two, three four and five (Philippe et al., 2011). The authors investigated climbing specific finger flexor strength and endurance, and the related muscular oxygenation kinetics in elite male and female climbers, as well as a control group of non-climbers. Following the design and protocol

of MacLeod et al. (2007), Philippe et al. (2011) measured endurance characteristics during sustained and intermittent contractions at 40% of MVC. Philippe et al. (2011) found that elite males had significantly higher MVCs compared to females. When comparing the two studies there appeared to be almost no strength differences between elite males and the intermediate climbers ( $491 \pm 76\text{N}$  vs  $485 \pm 65\text{N}$ , respectively). This could be due to both climbing groups having high best on-sight grades (22-27 vs. 28 Ewbank). Philippe et al. (2011) reported time-to-failure during the sustained contraction revealed no significant differences either between genders or between climbers and non-climbers. However, during the intermittent contractions the climbers performed for a significantly longer period of time than the non-climbers. There were no differences between genders or for the interaction of climbers/non-climbers x gender. In agreement with MacLeod et al. (2007), Philippe et al. (2011) suggested that the FTI was a better indicator of climbing specific endurance as it took into consideration maximal strength and endurance (time-to-failure). For the control groups, the sustained FTI of both studies were almost identical. The elite climbers appear to have lower values ( $17,443 \pm 2,878 \text{ NxS}$  (Philippe et al., 2011)) than the intermediate climbers ( $21,043 \pm 4474 \text{ NxS}$  (MacLeod et al., 2007)). During the intermittent contractions, the FTI appears to be very similar between intermediate ( $51,769 \pm 12,229 \text{ NxS}$ ) and elite ( $52,760 \pm 33,731 \text{ NxS}$ ) participants, however, the elites show a SD twice that of the intermediate climbers. With relation to the current study, the intermediate climbers described by MacLeod et al. (2007) are considered advanced and not elite, and so interpretation of their findings should be made with respect to the performance grade.



**Figure 8.1** An example of a NIRS trace showing the changes in muscle blood oxygenation during a sustained contraction. The black trace is the intermediate climber and the white trace is the non-climber. 0 denotes the start of the contraction and the black arrow denotes the point of release (MacLeod et al., 2007).



**Figure 8.2** An example of a NIRS trace showing the changes in muscle blood oxygenation during intermittent contractions. The black trace is the intermediate climber and the white trace is the non-climber. 0 denotes the start of contractions and the black arrow denotes the point of release (MacLeod et al., 2007).

Philippe et al. (2011) measured re-oxygenation during the intermittent contractions in the same rest phases as MacLeod et al. (2007), averaging the first, middle and last three phases. Similar to MacLeod et al. (2007) there were no significant differences between climbers and non-climbers in the first phase, but climbers had a significantly greater re-oxygenation during both the middle and last phases. MacLeod et al. (2007) reported de-oxygenation data for the sustained contraction at 20% time intervals throughout the length of the contraction period. The intermediate climbers significantly de-oxygenated the FDS to greater extent than the control group at 40, 60, 80 and 100% of the contraction. The authors suggested that this may have been due to a greater BF occlusion, or greater muscle fibre recruitment since the climbers obtained a greater MVC. The de-oxygenation profiles presented in Figure 8.1 shows how the non-climbers FDS de-oxygenated considerably at the start of the contraction, and slowly began to re-oxygenate throughout the contraction period. Whereas, the intermediate climbers de-oxygenated the FDS, and  $O_2$  levels remained low until the point of exhaustion. Philippe et al. (2011) reported a similar re-oxygenation profile of the FDP during the contraction, although the authors did not break sustained data down into 20% contraction periods.

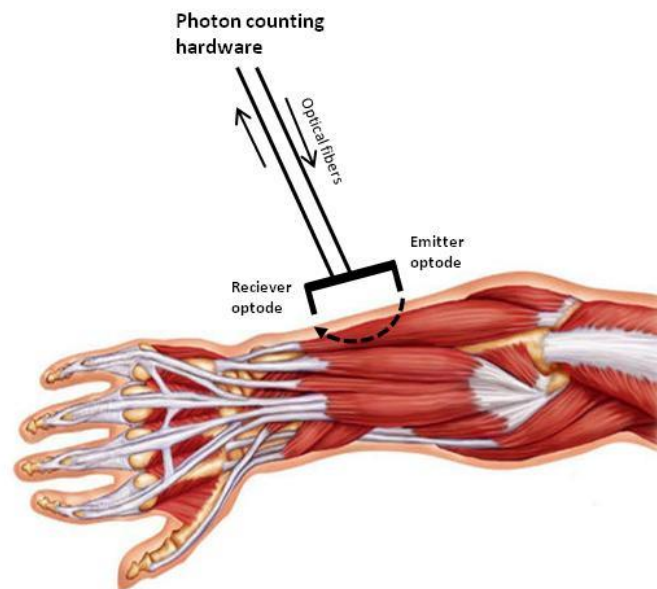
### **8.3.1 *The use of near infrared spectroscopy in muscle oxygenation***

In order to determine whether rock climbers have adaptations within the forearm flexors, the use of NIRS seems to be an appropriate tool due to its accuracy in non-invasively measuring tissue oxygenation.

Millikan (1937) was the first known person to use optics in assessing oxygenation in the soleus muscle of cats. The author developed instantaneous measurements of muscle metabolism whilst making simultaneous assessments of gas exchange. These use of optics was improved during the late 1950's and 1960's by Chance and Jöbsis (1959), and Chance and Weber (1963) who investigated oxygenation changes in the Sartorius muscle of frogs. The first human experimentation was conducted by Hampson and Piantadosi (1988) who investigated changes in HbO<sub>2</sub> in forearm skeletal muscle during tourniquet ischemia. However, over the best part of the last 73 years NIRS technology has dramatically improved. Although optical methods were used to investigate muscle metabolism for many years after the work of Millikan (1937), pre-1977 these were invasive techniques requiring surgery to expose the tissues (Boushel & Piantadosi, 2000). Jobsis (1977) demonstrated that NIRS could be used to assess the adequacy of O<sub>2</sub> provision and utilisation within living tissue.

As shown in Figure 8.3 NIRS is based upon the fact that light within the wavelength range 650-1000nm is absorbed by tissues, and the signal intensity change mainly due to the presence of haemoglobin. More specifically, one wavelength is sensitive to de-HbO<sub>2</sub> and another wavelength is sensitive to HbO<sub>2</sub>. Since light passed through the large vessels is mostly absorbed, light that reaches the detector on the optode comes mainly from the small blood vessels (arterioles, capillaries and venules) (Chance, Dait, Zhang, Hamaoka, & Hagerman, 1992; Dinler et al., 2007). Therefore, the signal provides a dynamic balance of information between the O<sub>2</sub> supply and consumption within the skeletal muscle.





**Figure 8.3 The path of near infrared light through the skin, adipose tissue and forearm muscle.**

The use of NIRS appears to be an appropriate tool for measuring tissue oxygenation kinetics in the forearm flexors of rock climbers during both exercise and recovery. This would allow for a greater understanding of possible training adaptations which may occur in climbers. Furthermore, it may help to explain whether resting on a climbing route, is beneficial to performance in different groups of climbers.

#### **8.4 Summary and aim**

It is clear that some attempt has been made to understand the oxygenation kinetics during sustained and intermittent contractions-to-failure in intermediate and elite male and female climbers. However, with the recent technological improvements in non-invasive assessments of tissue oxygenation and BF, it is surprising that no studies have focused on the  $O_2$  kinetics and BF responses during contractions, or the subsequent post-exercise recovery periods in rock climbers. Furthermore, no known attempt has been made to try and measure BF during the intermittent contractions or the release periods seen throughout a climbing ascent. Therefore, the aim of study two, was determine whether there were ability group differences in the oxygenation and BF dynamics of the forearm flexors (FDP and FCR), during and after sustained and intermittent contractions-to-failure at 40% of MVC.

## **8.5 Hypotheses**

- Elite climbers will have a greater FTI during both the sustained and intermittent contractions compared to the advanced, intermediate and control groups.
- The level of maximal de-oxygenation will increase with the concurrent increase in climbing ability during both sustained and intermittent contractions.
- Heart rate, BF and re-oxygenation during the relaxation periods of the intermittent contractions will increase with the concurrent increase in rock climbing ability.
- Re-oxygenation time to half recovery will decrease with the concurrent increase in rock climbing ability.

## **8.6 Strength of the study**

- The current study was able to measure oxygenation, blood velocities and HR simultaneously during contractions.
- The only known rock climbing study to assess oxygenation profiles in two forearm flexors simultaneously.
- The current study is the largest known investigation into the haemodynamic responses of the forearm flexors in rock climbers.
- The findings are unique to three specific ability groups of rock climbers.

## **8.7 Limitations**

Although careful consideration has been given to the methods, and pilot studies were conducted, there were still some limitations and delimitations within study two.

- It is assumed that the participants self-reported their best on-sight and red-point grades at the time of recruitment.
- It is assumed that all participants refrained from alcohol 24 hours and caffeine 2 hours prior to testing sessions, as requested.
- Due to the ultrasound device not having Duplex mode, it was not possible to record both the vessel velocity and diameters simultaneously.
- Due to the NIRS unit used, data was limited to a sampling rate of 4s.

- Data received from the NIRS device is of tissue oxygenation between the emitter and receiver on the optodes, and does not reflect solely muscle oxygenation.
- Although every measure was taken to accurately locate the FDP and FCR muscles, the precise position was difficult to identify.
- Elite climbers were classified as > 25 Ewbank and not > 29 as suggested in Appendix G. This was due to the lack of world class climbers in the greater Christchurch area.

## **8.8 Delimitations**

- Findings are representative of intermediate, advanced and elite male rock climbers
- Haemodynamic data is representative of contractions at 40% of MVC.
- Haemodynamic data during the intermittent contraction is specific to the contraction/rest phase cycle of 10s:3s.
- Post-exercise recovery data is unique to passive recovery only.

## Methods for Study Two

This chapter aims to provide an in depth account of the methodological strategies used to assess the haemodynamic changes in the forearm flexors. A rock climbing specific approach was employed to investigate possible differences between the groups: control, intermediate, advanced and elite. The subsections: *participants, apparatus design, software programming, body positing, procedures, warm-up, protocol, NIRS analysis, ultrasound, ultrasound transducer, ultrasound software* and *statistical analysis* will describe the methods used.

### 9.1 Participants

All participants were recruited via word of mouth from three local indoor rock climbing gyms: the Roxx Climbing Gym, the YMCA Climbing Gym and the University of Canterbury Rock Climbing Gym. All participants who made up the control group were recruited from the undergraduate and postgraduate student population at the University of Canterbury. The University of Canterbury Human Ethics Committee granted ethical approval for the study on 5/3/2012.

Over a 12-week period, 44 participants volunteered to take part in the testing. After the initial data screening was completed (post-exercise testing), six participants were removed due to technical errors with the NIRS equipment. A total of 38 participants were categorised into the four groups: control ( $n = 9$ ), intermediate ( $n = 9$ ), advanced ( $n = 10$ ) and elite ( $n = 10$ ). All rock climbing participants were placed into ability groups using the same self-report method (Appendix H) as study one (Chapter 5). The control groups were matched for age, height, weight and physical activity level. Climbing groups were subsequently checked for balance across age, gender, height and weight (as shown in Table 9.1). Significant differences between groups were reported for body fat percentage, years climbing, climbs per week, hours climbing per week, lead experience and best lead on-sight climbing grade.

**Table 9.1 Mean  $\pm$  SD for participant demographics and anthropometric data.**

	Control	Intermediate	Advanced	Elite	<i>F</i> value
Age (yrs)	26.22 $\pm$ 5.9	28.78 $\pm$ 4.41	26.8 $\pm$ 5.25	29.5 $\pm$ 9.44	0.530
Height (cm)	178.33 $\pm$ 7.25	177.78 $\pm$ 8.86	178.7 $\pm$ 7.38	174.6 $\pm$ 7.11	0.593
Weight (kg)	78.84 $\pm$ 11.21	79.56 $\pm$ 12.97	71.83 $\pm$ 10.27	69.33 $\pm$ 5.44	2.344
Body fat (%)	18.79 $\pm$ 10.69 <sup>*,**</sup>	20.26 $\pm$ 4.43 <sup>*,**</sup>	13.4 $\pm$ 4.2 <sup>*</sup>	12.06 $\pm$ 2.59	4.820
Years climbing (yrs)		6.33 $\pm$ 4.74 <sup>*,**</sup>	7 $\pm$ 3.97 <sup>*</sup>	13.4 $\pm$ 7.52	4.659
Climbs per week		1.31 $\pm$ 0.7 <sup>*,**</sup>	2.4 $\pm$ 0.67 <sup>*</sup>	2.85 $\pm$ 0.85	10.313
Hours climbing per week		2.9 $\pm$ 1.7 <sup>*,**</sup>	5.7 $\pm$ 2.28 <sup>*</sup>	8 $\pm$ 2.94	10.616
Lead experience (yrs)		5.61 $\pm$ 4.94 <sup>*</sup>	6.15 $\pm$ 4.12 <sup>*</sup>	12.9 $\pm$ 7.75	4.052
Best lead on-sight grade (Ewbank)		18.67 $\pm$ 1.32 <sup>*,**</sup>	21.7 $\pm$ 1.25 <sup>*</sup>	24.9 $\pm$ 0.74	72.661

\*\*\*\* Shows a significant difference ( $p < 0.05$ ) between the elite and all other groups

\*\*\* Shows a significant difference ( $p < 0.05$ ) between the advanced and the intermediate and control groups

\*\* Shows a significant difference ( $p < 0.05$ ) between the elite and the advanced and intermediate groups

\* Shows a significant difference ( $p < 0.05$ ) between the advanced and the intermediate group

## 9.2 Procedures

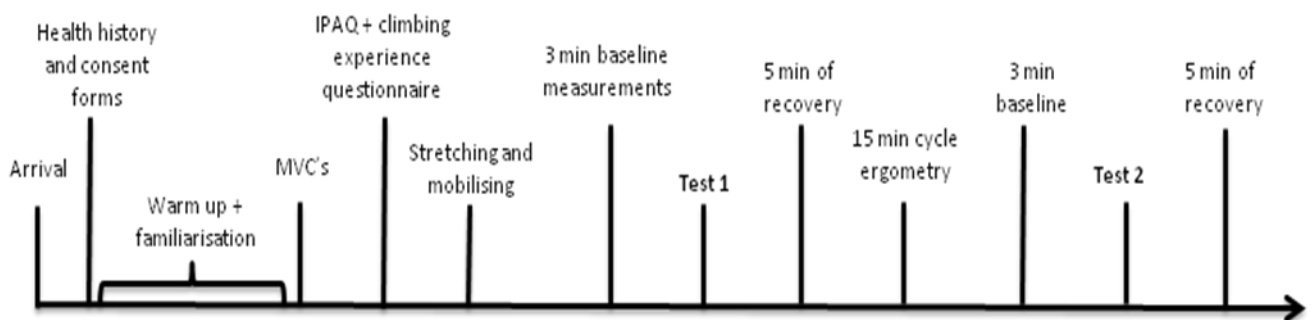
### 9.2.1 Warm-up and familiarisation

To ensure that all finger flexor muscles of the dominant hand were appropriately warmed up, all participants completed a standardised warm-up. The warm-up and familiarisation comprised of four main exercises. The first part consisted of six sustained sub-maximal contractions (5kg loads on the hold) on the apparatus. Each sustained contraction was held for a 10s period. A series of stretches and mobilisation exercises were then carried out. A series of intermittent contractions with the same 5kg load were then completed. In order to work as a warm up and a familiarisation activity, the intermittent contractions were the same as the main intermittent test (10s contraction and 3s rest). This was followed by a further set of stretches and mobilisation exercises all based around the hand and forearm flexors on the dominant side. Following this, the MVC trials were conducted. Each participant had three MVC trials each separated by a 30s rest period. If the highest score occurred on the third attempt, then a fourth contraction was allowed. Participants were asked to load the climbing hold with as much force as possible, and were verbally encouraged throughout each contraction.

### 9.2.2 Protocol

On arrival participants completed a health history consent form and medical questionnaire. This was followed by the warm up procedure and the MVC trials. To allow for recovery time after the MVC trials, the international physical activity questionnaire (IPAQ), climbing history and experience questionnaires were completed. Following this, participants were provided a few minutes to mobilise and stretch again before being fitted to the climbing apparatus. For the main two tests, all participants performed two maximal endurance contractions, a sustained contraction and an intermittent contraction (10s with 3s rest) both at 40% of MVC. During both trials, participants were verbally encouraged to contract for as long as possible. Each trial was separated by 20 minutes of light cycle ergometry at 40W and 30W for males and females respectively.

Before participants began each of their contractions, they were required to rest with their forearm in the upright position on the climbing hold for three minutes. During this time B-mode ultrasound was used to collect three 10s images for resting measures of brachial artery diameters. Following this, the pulsed-doppler ultrasound was used to collect a minute of blood velocity measures. Near infrared spectroscopy was also used in this three minute period to calculate baseline levels of muscle oxygenation in both the FDP and the FCR. The participant was then required to start the contraction (either the sustained or intermittent contraction) and continue until volitional fatigue. Following the cessation of exercise the participant was required to remain still and silent, in the upright position for five minutes of passive recovery. During this time continual measures of BF and re-oxygenation were recorded.



**Figure 9.1 Schematic of the testing protocol for study two.**

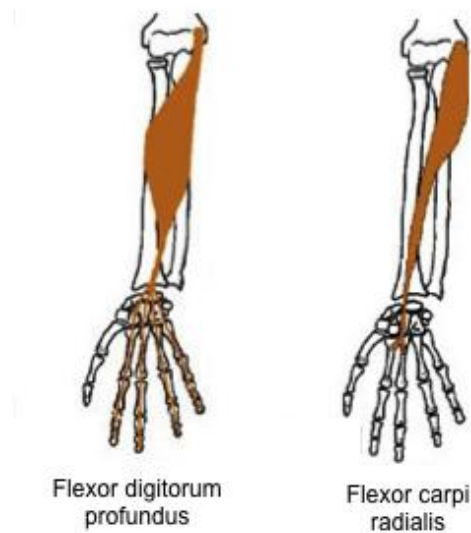
### **9.2.3 *Near infrared spectroscopy***

In recent years the use of NIRS has been used extensively within both sport science (Burelle & Hochachka, 2002; Nagasawa, 2008; Ogata et al., 2008; Pereira, Gomes, & Bhambhani, 2007) and health (Boushel et al., 2001; Dinler et al., 2007). The use of NIRS has been validated for measuring de-oxygenation and re-oxygenation during handgrip exercise at a range of intensities (10-90% MVC) (Van Beekvelt, Van Engelen, Wevers, & Colier, 2002). Van Beekvelt et al. (2002) suggested that NIRS was robust for the detection of skeletal muscle oxygenation over separate days, and at various workloads.

Study two used the NONIN 7600 (Plymouth, Minnesota, USA). This NIRS device has been previously validated for measuring changes in regional tissue oxygenation (Lobbestael, Roth, & Prior, 2009; MacLeod & Ikeda, 2009). Furthermore, the NONIN 7600 has been used in numerous clinical (Pantazopoulos et al., 2011; Scheeren, Schober, & Schwarte, 2012) settings, as well as being specifically used to assess tissue oxygenation kinetics in the forearm flexors (Schober & Schwarte, 2011).

Changes in oxygenation were recorded in two forearm muscles, the FDP and the FCR. The optodes were used and fitted in accordance with manufacturer guidelines. These optodes were held in place with medical tape and a crepe bandage to ensure no light interfered with the optodes. On each optode there were light emitters (LED) and light detectors (photodiode). The NIRS unit measures regional muscle tissue oxygenation based on the principles of the Beer-Lambert Law. The law relates the absorption of light to the properties of the material through which the light has passed. There is a logarithmic relationship between the concentration of compound, and the transmission of light through it. In the case of NIRS, by understanding the wavelengths of light, which are absorbed by the compounds HbO<sub>2</sub>, de-HbO<sub>2</sub>, the concentration of these different compounds can be determined. The effectiveness of the optodes is affected by the presence of excessive adipose tissue in the body. However, average body fat percentage was only 20.65%, 22.36%, 14.83% and 12.87% for the control, intermediate, advanced and elite groups respectively. Furthermore, the forearms are not a major site of fat storage within the body. Therefore, it can be assumed that excessive adipose tissue had no interference in data presented in study two.

The FDP was chosen as Philippe et al. (2011) suggested that it was the most important flexor muscle in the forearm as it bends the last (distal) joints of fingers two, three, four and five (used in the open crimp position). To locate the FDP muscle, a line was drawn on the anterior side of the forearm from the carpus to the medial epicondyle of the humerus. As suggested by Philippe et al. (2011), each participant performed a contraction on the climbing apparatus to locate the area of greatest contraction. The FCR was chosen since it is also an important finger flexor in the forearm, it attaches to the second and third fingers, and is used for contraction on a climbing hold which allows for an open crimp position. The FCR was located using the same technique as the FDP; however, the line was drawn on the posterior side of the forearm between the crease of the elbow and the carpus. These muscles are presented in Figure 9.2.



**Figure 9.2 Anatomical locations of the flexor digitorum profundus and the flexor carpi radialis.**





**Figure 9.3 Standardised set up for the assessment of haemodynamic responses in the dominant forearm.**

#### **9.2.4 *Ultrasound***

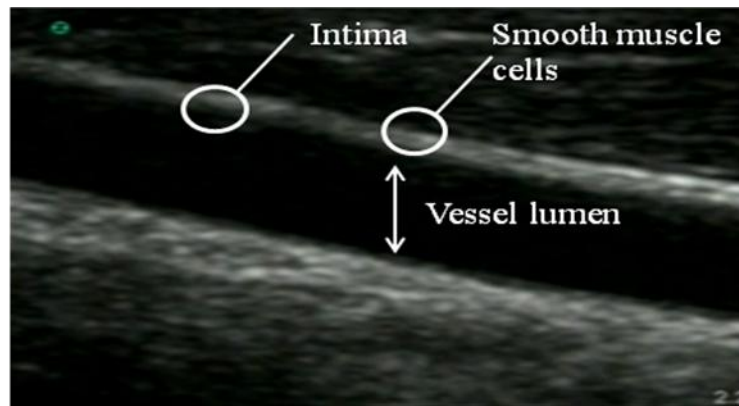
The SonoSite Micromax (FujiFilm, Washnigton, USA) ultrasound device was used to assess BF through the brachial artery (Figure 9.4). This machine did not possess true duplex functionality, which would have enabled simultaneous real time imaging (doppler) of blood velocity and arterial diameters (B-mode) throughout the brachial artery. Instead the operator had to change between the two settings, spending 60s recording velocities followed by 10s of diameters recording. This cycle (60s/: 10s) was continuously repeated for baseline measurements for the sustained and intermittent endurance tests, as well as throughout the five minute recovery period (post-cessation of exercise).



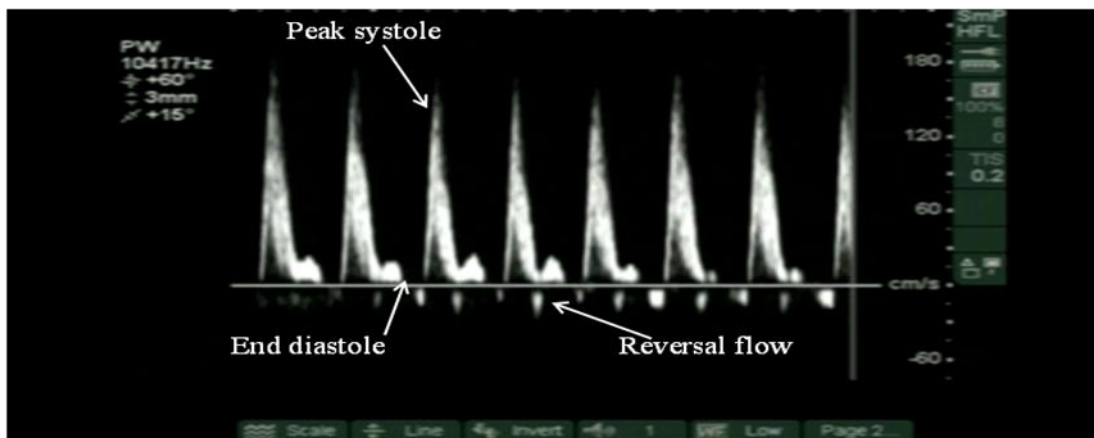
**Figure 9.4** The Sonosite Micromax ultrasound device fitted with an HFL3 8e probe which was used to assess both velocities and diameters in the brachial artery.

#### **9.2.5     *Ultrasound transducer***

Accurate analysis of BF is dependent on good quality images. In order to optimise the imaging of the vascular anatomical structures of the brachial artery, a SonoSite (HFL38e) broad-spectrum, 13-6 MHz linear array transducer (probe), with a scan depth of 6cm was used. The transducer was placed on the bicep of the upper arm (dominant side), so that a clear view of the brachial artery could be acquired (see Figure 9.3). Due to the apparatus design and the nature of the measurements during contractions it was almost impossible to use a commercially available fixed probe holder. Instead the ultrasonographer made measurements using a combination of an adapted probe clamp and freehand control. This set up allowed the probe to be held almost weight free whilst ensuring ease of fine adjustments of the angle and position. The sonographer had > 10 years experience, and has developed and validated several new techniques with regards to making assessments of the vasculature (Stoner & Sabatier, 2012a, 2012b). Ultrasound global (acoustic output, gain, dynamic range, gamma, and rejection) and probe-dependent (zoom factor, edge enhancement, frame averaging, and target frame rate) settings were standardised in accordance with Stoner, West, Cates, and Young (2011).



**Figure 9.5** Brachial artery viewed as B-mode image. The artery image was used for analysis of vessel diameter for determination of total forearm blood flow.



**Figure 9.6** Velocity waveforms viewed with Doppler ultrasound. Velocities were used for determination of total forearm blood flow. Horizontal white line represents a velocity of '0'.

#### **9.2.6** *Ultrasound software*

Data were collected as uncompressed AVI files using a generic USB 2 video capture device sampling at 30 frames per s. All images were recorded and stored on a laptop which was fitted with an appropriate graphics board and software for: data capture (Ulead Systems Inc, Taiwan), video de-compilation (Blaze Media Pro, version 7.0, Mystik Media) and image analysis (semi-automated edge-detection custom software).

### **9.3 Blood flow analysis**

#### **9.3.1 Velocities**

All resting and exercise velocities were analysed using a custom written MatLab (2011b) program. Images (examples presented in Figure 9.6) of each five second waveform section were displayed and double checked to ensure all data was shown in the same scale. Pixel ratio was then defined (default = 40); if an image contained some noise then a lower pixel ration was used to ensure appropriate capture of data. The Y axis maximum, baseline and minimum points were defined on the graph as well as time, zero and five on the X axis. This was done in order for the software to recognise the background sample and consequently identify the waveforms within the image. Waveform images were then read and converted into an Excel file before a maximum velocity vs time graph could be produced. Averages were then calculated for: HR, velocity at rest, velocity during contraction and between contractions (for intermittent test only). This process was used for both sustained and intermittent contractions. Mean diameter and velocities were recorded and averaged over three resting trials.

#### **9.3.2 Diameters**

Diameters (Figure 9.5) were broken down using Avidemux version 2.5.6-1 (Mean, Grunster & Fahr Programmers). Three 10s video clips for both sustained and intermittent contractions were taken for measurements of resting vessel diameters (baseline). In accordance with Stoner et al. (2006) and Sabatier, Stoner, Reifenberger, and McCully (2006) the 10s video clips were broken down into one image per frame, resulting in approximately 350 images per video. Lab View Image Analyser 24 was then calibrated to the SonSonite ultrasound pixel ratio before being used to read artery (vessel) diameters; these vessels must be horizontal before being accurately read by the program. In order to do this, a straight line was drawn parallel to one of the vessel walls; this was compared to the second vessel wall to insure the entire artery was located, and the image could be rotated into a fully horizontal position. Image analysis was then run and exported into Microsoft Excel (Microsoft Excel, Version 2007). The routine validated by Stoner, Faulkner, Fryer, and Lambrick (2013) was used to define the high

and low peaks of systole and diastole throughout each cardiac cycle. Data points for HR, peak systole and diastole were averaged across each clip.

### 9.3.3 Blood flow calculation

Blood flow through the brachial artery was calculated based on the following equation:

$$\text{Area of the vessel (mm)} = \text{Pi} \times \frac{\left[ \frac{\text{Diameter mean (mm)}}{2} \right]^2}{100}$$

Pi = 3.14

**Figure 9.7 Equation for determining blood flow (Stoner et al., 2011).**

## 9.4 Fingerboard apparatus design

The fingerboard apparatus was developed at the University of Canterbury, New Zealand and was based on the designs from MacLeod et al. (2007) and Philippe et al. (2011). The apparatus was designed as a rock climbing specific handgrip dynamometer, which could measure strength that mimicked, as closely as possible, that produced from an open crimp as seen during indoor rock climbing. For comparability reasons to Philippe et al. (2011), and MacLeod et al. (2007) the modifications consisted of removing grip tape from the wooden board and replacing this with a modular rock climbing hold (Uprising Ventures, Christchurch, New Zealand) as this was suggested by Philippe et al. (2011) to be an important limitation of their study. The wire cable that connected the strain gauge to the wooden ledge was replaced with a 12mm threaded aluminium rod, which had virtually no flexibility and no horizontal movement. However, it could be screwed up or down the rails so that the climbing hold could be fitted to each participants forearm length. The 12mm aluminium rod was connected to an AST 500 strain gauge (Precision Transducers Ltd, Australia), which was accurate to 0.01kg. The strain gauge was then connected to a computer system, which was specifically programmed for this study. In order to determine the reliability of the device, fifteen

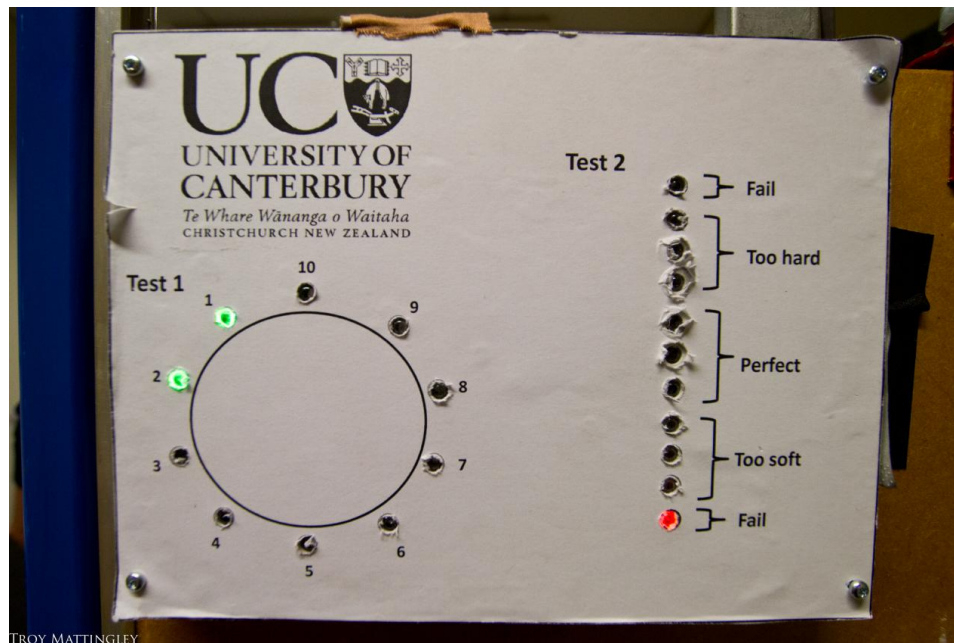
male participants performed three MVC trials on two separate days. Coefficient of variations for the duplicates was 0.5 % (Appendix D).

#### **9.4.1 *Software programming***

The software was designed and written by Mitchell Systems Ltd (Christchurch, New Zealand) to match as closely as possible those of MacLeod et al. (2007) and Philippe et al. (2011). The digital/analog conversion was written based on an ADS1232, 24-bit delta sigma precision, low noise, analog to digital converter (Texas Instruments, Texas, USA). The program was written in source code C, and was further modified using Code Compressor Studio V5 (Texas Instruments, Texas, USA). The development board, which gave the different timing settings and test modes was programmed with an Olimex MSP430-JTAG-RF, wireless USB JTAG (Plovdic, Bulgaria).

The four test modes that were programmed into the software were: 1) practice/warm-up trial, 2) MVC, 3) sustained contraction test, and 4) intermittent contraction test. During all four modes, feedback was provided to the participant via a series of LED lights (see Figure 9.8). The practice/warm-up trial consisted of undertaking the intermittent trial (loading the climbing hold for 10s and unloading for 3s) at a set weight of 5kg. The MVC trial was programmed such that all participants were given three attempts to attain their MVC, if the strongest contraction occurred on the third attempt, then a fourth try was given. During the sustained and intermittent isometric contractions the participants were given feedback via a series of LED lights as a traffic light system. This feedback traffic light system was based on the ones used by MacLeod et al. (2007) and Philippe et al. (2011). The middle green light showed that exactly 40% of MVC was being loaded through the hold. The two LED lights either side of the central green light were amber, and the singular outer lights were red, these lights represented the 5% deviation error from the 40% MVC. If either of the red lights were illuminated for 2s or more then the computer automatically ended the trial. During the intermittent contraction mode only, a cylindrical set of LED's numbered 1-10 were illuminated, these then counted down at one per second so that the participant knew how long to contract for (see Figure 9.8). During the three seconds of recovery time, the lights flashed on LED's 1, 5 and 10 to represent the recovery time before the next 10s contraction began; this process was repeated until exhaustion occurred. As preliminary studies showed that it was difficult for the participant to concentrate on the timing lights when they were near exhaustion,

the tester additionally, verbally communicated the timings by telling the participant when to contract and when to relax.

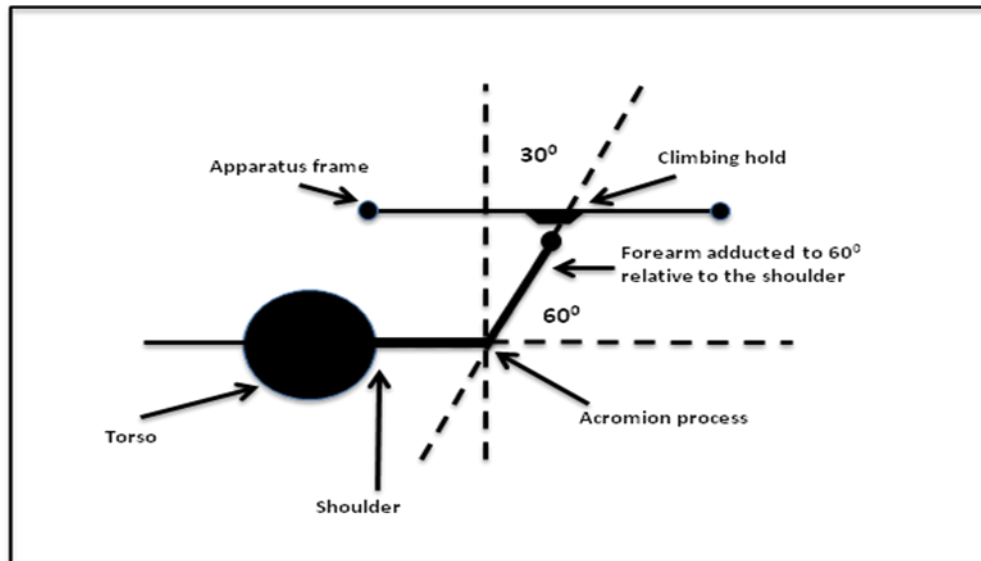


**Figure 9.8 The LED lighting system which provided feedback to the participants during the sustained and intermittent tests.**

#### **9.4.2 Body positioning**

Seating and arm position (exercising arm) was almost identical to that described by MacLeod et al. (2007) and Philippe et al. (2011). Participants were seated on a standard chair in a position that elicited at 90° bend at the elbow joint. The upper arm was adducted to 60° from the shoulder girdle axis and placed onto the rest platform. A wooden block was mounted to the resting platform to prevent the participants from abducting their arm during the contractions. The fingers of the dominant hand were placed onto the climbing hold in an open crimp position. Unlike the studies by MacLeod et al. (2007) and Philippe et al. (2011) participants in study two were not allowed to use their non-exercising arm to block under the table as it was thought that this would allow for other muscles to be engaged in a way that is not natural to the sport. Instead, participants were asked to place their hand on their knee throughout the tests. To ensure that the grip was as sport specific as possible, a modular hold was used which only allowed the distal phalanges of the index, middle, ring and little finger to be

used. As with the open crimp position, the thumb was not used throughout the contraction.



**Figure 9.9** Schematic of a participant's position on the climbing apparatus (transverse plane).

### 9.5 Statistical analysis

Analysis was performed using Statistical Package for Social Sciences (SPSS, Version 20.0), R-Project, and Microsoft Excel (2007). All data is presented as mean  $\pm$  SD unless otherwise stated. For all statistical analysis the critical  $\alpha$ -level was set at 0.05 and Bonferroni adjustment was used when appropriate. If an independent variable could be determined from two other variables being analysed, i.e. recovery *time* and the *amount* of recovery can determine the *rate* of recovery; then no analysis was performed on one of these variables. This was done in order to not repeat analyses.

Before analysis was conducted all variables were assessed for normal distribution using the Kolmogorov-Smirnov goodness-of-fit test, as well as checking for equal variance by visually examining the change in variance across the means (if the maximum variance was less than three times the minimum variance then equal variance was assumed). For every independent variable a series of ANCOVA's were performed, the covariates were: height, weight, age, skeletal muscle mass and body fat percentage. None of the covariates were found to significantly affect any of the participant's scores.



As the ANCOVA revealed there were no significant effects on the FDP or the FCR during the sustained or intermittent contractions, or their subsequent post-recovery periods, analysis reverted to using a simpler ANOVA for each variable of interest. To control the increasing error rate due to multiple testing with so many independent variables, a global MANOVA test for a difference in means across all groups was carried out first. This was followed by an ANOVA for each independent variable in all cases where a significant MANOVA test statistic was found. Bonferroni correction was determined by multiplying the  $p$  statistic by the number of independent variables entered into the MANOVA, if the  $p$  statistic remained less than 0.05 then it was considered statistically significant. Where a significant test statistic was found, post-hoc LSD testing followed each ANOVA to explore the source of the differences in the mean between the groups, whilst also controlling for the error rate (CI's are presented from the LSD intervals which were set at 95%). For all  $t$ -tests Bonferroni correction was used to adjust the  $p$  statistic (the  $p$  value was multiplied by the number of tests performed).

As previously explained in Chapter 9, during this study a five minute recovery period was used in order to ensure capture of full recovery. However, for the FDP muscle only the advanced and elite groups had all participants fully recover within this five minute period. In the control and intermediate groups, there were only four participants which fully recovered. Furthermore, the FCR muscle had even lower rates of recovery. Only the entirety of the elite group fully recovered. The control, intermediate and advanced groups had only four, three and seven (respectively) participants fully recover within the five minute period. Therefore, as the data set is incomplete, no statistical analyses have been performed on any full recovery characteristics but means  $\pm$  SD are reported in Appendix C.

### **9.5.1 Sustained contraction**

To determine if there were differences between ability groups on the combined independent variables a series of MANOVA's were conducted on the following groups of data: IPAQ (section 10.1), strength and endurance characteristics (10.2 and 10.3) de-oxygenation characteristics (10.6), half recovery characteristics on the FDP and FCR (10.7) as well as blood velocity (10.12.1), BF (10.12.2) and HR characteristics (10.12.3). In the cases of the independent variables IPAQ questions (10.1), strength and

endurance characteristics (10.2 and 10.3) and half recovery characteristics (10.7), there was strong asymmetry across the variables and so ANOVA assumptions were not robust. In these cases data was log transformed before MANOVA and ANOVA were conducted. Where MANOVA revealed significant differences a series of one-way ANOVA's were used to determine if there were differences present between ability groups for each independent variable. Where significant differences between groups were found, subsequent post-hoc analyses (LSD or independent *t*-test models) were conducted to determine where the difference may lay.

### **9.5.2 Intermittent contraction**

To determine if there were differences between ability groups on the combined independent variables a series of MANOVA's were conducted on the following groups of data: strength and endurance characteristics (section 10.8.1), contraction phase de-oxygenation (10.8.2), *relative* re-oxygenation  $\Delta$  rest phases (10.9.2), *absolute* re-oxygenation rest phases (10.9.1), half recovery recovery characteristics (10.11) and BF (10.12). In the cases of the independent variables: strength and endurance characteristics (10.8.1), and half recovery characteristics (10.11), the variance was either greater than three times the mean or had close asymmetry and so ANOVA assumptions were confounded. In these cases data was log transformed before MANOVA and ANOVA were conducted. Where MANOVA revealed significant differences a series of one-way ANOVA's were used to determine if there were differences present between ability groups for each independent variable. Where significant differences between groups were found, subsequent post-hoc analyses (LSD or independent *t*-test models) were conducted to determine where the difference may lay.

## 9.6 Summary

The participant grouping variables were the same as those reported in Chapter 5 (study one) ensuring accurate and valid comparisons could be made. The method for study two allows for a unique sport specific approach to the understanding of conduit artery BF and O<sub>2</sub> kinetics within the forearm flexors of multiple ability groups of rock climbers. The study design allows for the replication of the work by MacLeod et al. (2007) and Philippe et al. (2011), whilst improving and expanding not only on the range of ability groups investigated, but understanding the *absolute* and *relative* re-oxygenation during contractions-to-failure, as well as the novel assessments of oxygenation time to half recovery, BF and HR responses. The following chapter ‘Results for Study Two’ presents data with appropriate statistical analyses to ensure valid interpretations could be made in Chapter 11. These interpretations are with respect to de-oxygenation and re-oxygenation of the FDP and FCR, total forearm BF and HR responses, both during and after sustained and intermittent contractions to failure.

## Results for Study Two

Results from this study have been sub-divided into two main sections, assessment of oxygenation and BF responses in the forearm flexors during and after 1) a sustained volitional contraction at 40% of MVC, and 2) intermittent contractions until volitional fatigue, at 40% of MVC. These two sections help to depict the main haemodynamic changes within the forearm flexors of different ability rock climbers during both exercise and recovery.

### 10.1 Physical activity questionnaire

As previously indicated in Chapter 9, before any testing was carried out, each participant completed the shortened version of the IPAQ (Booth et al., 2003). Table 10.1 presents mean  $\pm$  SD as well as  $F$  and  $p$  values (one-way ANOVA) for all the items within the questionnaire. For responses to the questions there appears to be minimal differences between the groups. The control group spend less time exercising, as seen in the responses to ‘time spent vigorously’ and ‘moderately exercising’ as well as ‘walking per day’.

**Table 10.1 Mean  $\pm$  SD  $F$  and  $p$  values for the responses to the International Physical Activity Questionnaire in all ability groups.**

Questions	Control	Intermediate	Advanced	Elite	$F$ value (df)	$p$ value
Days vigorous exercise per week	2.44 $\pm$ 2.35	3.83 $\pm$ 1.96	2.5 $\pm$ 1.58	2.3 $\pm$ 1.16	1.503 (3,34)	0.241
Time vigorous exercise per day	0.97 $\pm$ 0.99	2.03 $\pm$ 1.61	2.28 $\pm$ 1.09	1.95 $\pm$ 1.07	0.786 (3,36)	0.515
Days moderate exercise per week	3.67 $\pm$ 3.16	3.22 $\pm$ 2.59	3.30 $\pm$ 2.1	2.5 $\pm$ 1.84	2.954 (3,34)	0.055
Time moderate exercise per day <sup>+</sup>	0.56 $\pm$ 0.73	1.25 $\pm$ 0.8	1.28 $\pm$ 1.47	1.4 $\pm$ 1.63	0.305 (3,33)	0.822
Days walking for 10 min + per week	3.13 $\pm$ 2.64	3.86 $\pm$ 2.48	3.67 $\pm$ 2.92	4.7 $\pm$ 2.54	0.679 (3,30)	0.574
Time spent walking per day <sup>+</sup>	0.29 $\pm$ 0.25	3.7 $\pm$ 6.36	2.05 $\pm$ 2.41	1.69 $\pm$ 2.39	1.121 (3,28)	0.362
Time spent sitting per day	6.59 $\pm$ 4.2	4.88 $\pm$ 3.3	6.20 $\pm$ 3.02	5.15 $\pm$ 2.67	0.901 (3,33)	0.456

<sup>+</sup> Represents data which has been log transformed before performing data analyses

A one-way between groups MANOVA was performed to investigate ability group differences in responses from the IPAQ. The responses to each question were used as dependent variables. The independent variable was ability group. There was a non-significant difference between groups on the combined dependent variables ( $F_{(21,63)} = 0.914$ ,  $p = 0.576$ ; Pillai's Trace 0.787).

## 10.2 Strength characteristics

As can be seen in Table 10.2 mean  $\pm$  SD suggest that MVC increased with level of ability, despite decreases in body weight (anthropometric characteristics reported in Table 9.1). When strength is normalised to body mass (MVC/body mass), the same pattern occurred as with the MVC, the elite climbers had the highest strength-to-weight ratio.

**Table 10.2 Mean  $\pm$  SD forearm strength characteristics in all ability groups.**

	Control	Intermediate	Advanced	Elite
MVC (N)	245.17 $\pm$ 59.59	273.27 $\pm$ 71.84	298.77 $\pm$ 57.4	412.22 $\pm$ 141.34**
MVC/body mass (N/kg)	3.21 $\pm$ 1.05	3.42 $\pm$ 0.58	4.16 $\pm$ 0.61	5.9 $\pm$ 1.81***

\*\*\* Shows significant differences ( $p < 0.05$ ) between the elite and all other groups.

\*\* Shows significant differences ( $p < 0.05$ ) between the elite and the control and intermediate groups

MVC = maximal voluntary contraction, N = newton, N/kg = newtons divided by kilograms

A one-way between groups MANOVA was performed to investigate ability group differences in the strength characteristics during the sustained contraction. Three dependent variables were used: MVC, MVC/body mass and FTI. The independent variable was the ability group. There was a significant difference between ability groups on the combined dependent variables ( $F_{(9,102)} = 3.569$ ,  $p = 0.001$ ; Pillai's Trace 0.718). Mean  $\pm$  SD values for strength characteristics are reported in Table 10.2. In order to avoid repetition, length of contraction was omitted from the statistical analyses as this can be calculated from the O<sub>2</sub> saturation drop (section 10.6.1) and O<sub>2</sub> saturation drop  $\cdot$  s (section 10.6.2).

After the preliminary MANOVA revealed significant differences in the strength characteristics, a one-way ANOVA was used to assess for differences in MVC between the four groups. The estimated variance explained by the mean effects within each group for the MVC was 36%. After log transformation, a significant difference was found between groups ( $F_{(3,34)} = 5.787, p = 0.009$ ). Post-hoc LSD indicated that the elite group were significantly stronger than the control (mean difference = 167.4, CI 54.60 – 279.48) and intermediate groups (mean difference = 138.95, CI 26.51 – 251.39), but not the advanced (mean difference = 113.44, CI 4.0 – 222.89) group. After log transformation a significant difference in MVC/body mass (N/kg) was found between ability groups ( $F_{(3,34)} = 10.924, p < 0.0005$ ). The estimated variance explained by the mean effects within each group for MVC/body mass (N/kg) was 49%. Post-hoc LSD indicated that the elite group was significantly stronger than the control (mean difference = 2.68, CI 1.27 – 4.10), intermediate (mean difference = 2.47, CI 1.056 – 3.89) and advanced (mean difference = 1.73, CI 0.35 – 3.11) groups (Table 10.2).

### 10.3 Sustained endurance characteristics

As previously mentioned, (section 10.2) in order to avoid repetition the length of contraction was omitted from statistical analyses. As can be seen from Table 10.3 the length of sustained contraction appears to vary across the ability groups. Mean  $\pm$  SD suggest the control and elite groups had a similar length of contraction which was shorter than both the intermediate and advanced groups. All SD's are large suggesting a variety of contraction lengths within each ability group. The mean  $\pm$  SD FTI appears to have been higher in all climbing groups compared to the control group. A one-way ANOVA revealed this difference to be non-significant ( $F_{(3,34)} = 2.199, p = 0.318$ ).

**Table 10.3 Mean  $\pm$  SD forearm endurance characteristics during the sustained contraction in all ability groups.**

	Control	Intermediate	Advanced	Elite
Length of contraction (s)	107.11 $\pm$ 43.02	175.11 $\pm$ 105.31	141.2 $\pm$ 56.44	102.4 $\pm$ 38.97
Force time integral (N x s)	10799 $\pm$ 5882	17391 $\pm$ 5933	16826 $\pm$ 7435	15605 $\pm$ 4830

s = seconds, N x s = Newton's multiplied by seconds

#### 10.4 Baseline blood flow characteristics

In order to determine differences in BF characteristics during the sustained and intermittent contractions, resting baseline values had to be ascertained. Baseline values for vessel area, diameter, velocity, BF and HR are presented in Table 10.4.

**Table 10.4 Mean  $\pm$  SD  $F$  and  $p$  values for baseline measurements of vessel diameter and area, as well as velocity, blood flow and heart rate before sustained and intermittent contractions.**

	Control	Intermediate	Advanced	Elite	$F$ value df 3,33	$p$ value
Vessel diameter (mm)	$4.25 \pm 0.51$	$4.53 \pm 0.32$	$4.57 \pm 0.65$	$4.34 \pm 0.48$	1.031	0.465
Velocity (mm $\cdot$ s)	$23.76 \pm 11.49$	$23.7 \pm 5.92$	$18.48 \pm 4.67$	$23.68 \pm 8.77$	0.738	0.345
Vessel Area (mm <sup>3</sup> )	$0.14 \pm 0.03$	$0.16 \pm 0.02$	$0.17 \pm 0.05$	$0.15 \pm 0.03$	1.093	0.495
BF (mL $\cdot$ min <sup>-1</sup> )	$202 \pm 109$	$227 \pm 49$	$192 \pm 63$	$218 \pm 105$	0.281	0.135
HR (bts $\cdot$ min <sup>-1</sup> )	$65.9 \pm 12.39$	$63.02 \pm 15.04$	$68.03 \pm 15.04$	$70.65 \pm 11.63$	0.471	0.225

BF = blood flow, HR = heart rate

In order to assess whether ability group differences existed in baseline BF characteristics, resting diameter, area, velocity, BF and HR were investigated. A one-way between groups MANOVA was performed to investigate ability group differences in resting BF characteristics through the brachial artery. Five dependent variables were used: Vessel diameter, velocity and area, as well as HR and BF. The independent variable was ability group. There was a non significant difference between ability groups on the combined dependent variables ( $F_{(15,84)} = 1.089$ ,  $p = 0.379$ ; Pillai's Trace 0.489).

#### 10.5 Sustained forearm blood flow characteristics

In order to assess ability group differences in BF characteristics during the sustained contraction, mean change in velocity, total forearm BF and HR were investigated. Mean change is determined by the difference between resting values sampled at baseline and those sampled during the last minute (minute average) of exercise.

### 10.5.1 Mean change in velocity and blood flow

Mean  $\pm$  SD presented in Table 10.5 suggests there was a trend for increased mean change in velocity with ability group. As climbing ability increased so did the velocity seen during the sustained contraction. The mean change in BF was relatively similar in both the control and intermediate groups, these values were notably lower than those seen in the advanced and elite groups, who had a similarly high BF during the contraction. Data presented within Table 10.5 suggests that during the last minute of the sustained contraction the advanced and elite groups had a higher mean change in HR than the control and intermediate groups.

**Table 10.5 Mean  $\pm$  SD  $F$  and  $p$  values for the change in velocity, blood flow and heart rate measured in the brachial artery during the last minute of sustained contraction.**

	Control	Intermediate	Advanced	Elite	$F$ value (df)	$p$ value
Mean change in velocity (mm $\cdot$ s)	18.76 $\pm$ 9.2	17.87 $\pm$ 10.4	25.87 $\pm$ 13.56	27.82 $\pm$ 17.23	1.333 (3,30)	0.284
Mean change in BF (mL $\cdot$ min <sup>-1</sup> )	156 $\pm$ 79	179 $\pm$ 113	270 $\pm$ 162	262 $\pm$ 193	1.359 (3,30)	0.276
Mean change in HR (bts $\cdot$ min <sup>-1</sup> )	23.48 $\pm$ 12.47	23.78 $\pm$ 16.3	33.92 $\pm$ 16.58	35.21 $\pm$ 15.8	1.196 (3,27)	0.333

*The mean change in velocity HR and BF is the difference between baseline values and the last minute of exercise. BF = blood flow, HR = heart rate*

Although Table 10.5 suggests that there were differences between ability groups for the mean change in velocity, HR and BF, a one-way MANOVA revealed non-significant differences ( $F_{(6,54)} = 0.999$ ,  $p = 0.435$ ; Pillai's Trace 0.200) on the combined dependent variables (mean change in velocity and BF). Although Table 10.5 suggests that there may have been ability group differences in the mean HR change, a one-way ANOVA revealed these to be non-significant.



## 10.6 De-oxygenation characteristics

Two, one-way between groups MANOVA's were performed to investigate ability group differences in oxygenation characteristics during the sustained contraction for both the FDP and the FCR muscles. Two dependent variables were used: oxygenation drop and oxygenation drop ·s. The independent variable was ability group. For the FDP muscle, there was a significant difference between ability groups on the combined dependent variables ( $F_{(6,68)} = 4.231$ ,  $p = 0.001$ ; Pillai's Trace 0.544). For the FCR there was also a significant difference between ability groups on the combined dependent variables ( $F_{(6,68)} = 2.093$ ,  $p = 0.014$ ; Pillai's Trace 0.408).

**Table 10.6 Mean  $\pm$  SD tissue de-oxygenation and re-oxygenation characteristics immediately post sustained contraction in the flexor digitorum profundus and flexor carpi radialis of intermediate, advanced and elite climbers as well as non-climbers.**

	Total $\Delta$ oxygenation % drop	Total oxygenation % drop ·s	Half O <sub>2</sub> % debt upon release	Time to half recovery s	Half O <sub>2</sub> % rise ·s
<b>FDP</b>					
Control	32 $\pm$ 14.27*	0.32 $\pm$ 0.14*	15 $\pm$ 7.09	94.71 $\pm$ 63.15	0.25 $\pm$ 0.21*,**
Intermediate	34.33 $\pm$ 9.49*	0.27 $\pm$ 0.22*	18.67 $\pm$ 3.77	46.66 $\pm$ 32.25	0.68 $\pm$ 0.52*,**
Advanced	42.8 $\pm$ 9.33*	0.34 $\pm$ 0.14*	22.1 $\pm$ 5.93	11.98 $\pm$ 8.88****,***	2.87 $\pm$ 1.89
Elite	63.1 $\pm$ 17.55	0.77 $\pm$ 0.55	32.3 $\pm$ 8.49	8.44 $\pm$ 3.39****,***	4.51 $\pm$ 2.2
<b>FCR</b>					
Control	22.67 $\pm$ 16.78	0.23 $\pm$ 0.16	10.91 $\pm$ 8.69	30.36 $\pm$ 25.31	0.39 $\pm$ 0.36
Intermediate	14.56 $\pm$ 7.76*	0.1 $\pm$ 0.06*	7.64 $\pm$ 4.28	97.26 $\pm$ 64.99	0.12 $\pm$ 0.14
Advanced	28.9 $\pm$ 15	0.23 $\pm$ 0.16	14.49 $\pm$ 7.3	15.49 $\pm$ 18.08***	1.83 $\pm$ 1.93
Elite	36.5 $\pm$ 0.43	0.43 $\pm$ 0.26	18.6 $\pm$ 4.67	6.83 $\pm$ 4.94***	4.68 $\pm$ 4.14

Half O<sub>2</sub>% debt upon release describes the amount of O<sub>2</sub> which needs to be paid back to return O<sub>2</sub> to baseline values. It is determined from the O<sub>2</sub>% at the point of release (handgrip failure) and not maximal de-oxygenation, as this may have occurred previously during the contraction (see Figure 8.1 and Figure 8.2). FDP = flexor digitorum profundus, FCR = flexor carpi radialis,  $\Delta$  = delta value.

\*Shows the group is significantly different ( $p < 0.05$ ) from the elite group

\*\*Shows the group is significantly different ( $p < 0.05$ ) from the advanced group

\*\*\*Shows the group is significantly different ( $p < 0.05$ ) from the intermediate group

\*\*\*\*Shows the group is significantly different ( $p < 0.05$ ) from the control group

### **10.6.1 Total oxygenation drop**

When observing the amount of de-oxygenation within the FDP muscle during the sustained contraction, it appears that as climbing ability increased, so did the maximal amount of O<sub>2</sub> used during the contraction. This was particularly so for the elite group who experienced a notably large drop. Mean  $\pm$  SD presented in Table 10.6 suggest the oxygenation drop within the FCR was less in all ability groups when compared to the FDP muscle. The differences between the FDP and FCR muscles appeared to be smallest within the control group. As with the FDP muscle, the drop in oxygenation in the FCR appears to increase between the intermediate and elite groups. However, unlike the FDP muscle, the FCR in the control group appeared to de-oxygenate more than the intermediate group, but less than the advanced.

A series of one-way ANOVA's were used to assess for potential differences in the oxygenation drop between ability groups in both the FDP and FCR during the sustained contraction. There was a significant difference ( $F_{(3,34)} = 11.115, p < 0.0005$ ) between the groups. The estimated variance explained by the mean effects within each group for the FDP was 50%. Post-hoc LSD indicated that for the FDP muscle, the elite group de-oxygenated significantly more than the control (mean difference = 31.1, CI 14.74 – 47.46), intermediate (mean difference = 28.77, CI 12.41 – 45.13) and advanced (mean difference = 20.3, CI 4.38 – 36.22) groups. For the FCR there was also a significant difference between the ability groups ( $F_{(3,34)} = 4.715, p = 0.014$ ). The estimated variance explained by the mean effects within each group was 29%. Post-hoc analyses indicated that in the FCR the elite group de-oxygenated significantly more than the intermediate (mean difference = 21.94, CI 5.56 – 38.33) but not the control (mean difference = 2.54 – 30.22) or advanced (mean difference = 7.6, CI 8.35 – 23.55) groups.

### **10.6.2 Total oxygenation drop per second**

When observing the O<sub>2</sub>% used per second within the FDP, the control, intermediate and advanced groups appeared to de-oxygenate by similar quantities per second throughout the contraction (as shown in Table 10.6). The O<sub>2</sub>% that the elite group de-oxygenated per second was notably greater than all other groups. Mean  $\pm$  SD in Table 10.6 suggests all groups had a smaller per second decrease in O<sub>2</sub>% in the FCR compared to the FDP. Within the FCR the intermediate group had the smallest per

second decrease in  $O_2\%$ , whereas the control and advanced groups appeared to de-oxygenate at similar rates. Similar to the FDP, the FCR in the elite group had the greatest per second decrease in  $O_2\%$  during the sustained contraction (although not to the extent seen in the FDP).

A series of one-way ANOVA's were used to determine if there were differences between ability groups in the oxygenation drop ·s in both the FDP and FCR during the sustained contraction. For the FDP there was a significant difference between ability groups ( $F_{(3,34)} = 5.133, p = 0.01$ ). The estimated variance explained by the mean effects within each group for the FDP was 31%. Post-hoc LSD indicated that the elite group de-oxygenated significantly more ·s than the control (mean difference = 0.45, CI 0.56 – 0.84), intermediate (mean difference = 0.5, CI 0.10 – 0.89) and advanced (mean difference = 0.43, CI 0.41 – 0.81) groups. For the FCR there was a significant difference between the ability groups ( $F_{(3,34)} = 5.429, p = 0.008$ ). The estimated variance explained by the mean effects within each group was 32%. Post-hoc LSD indicated that the  $O_2\%$  drop ·s within the FCR of the elite group was significantly greater than the intermediate group only (mean difference = 0.32, CI 0.10 – 0.55). Although mean  $\pm$  SD in Table 10.6 suggests there may have been differences in  $O_2\%$  drop ·s within the FCR, unlike the FDP the elite group did not significantly de-oxygenate within the FCR more ·s than the control (mean difference = 0.2, CI 0.02 – 0.42) or advanced (mean difference = 0.2, CI 0.02 – 0.41) groups (Table 10.6).

### **10.6.3 Half muscle oxygen debt**

Table 10.6 presents half of the  $O_2$  debt created during the sustained contraction, defined as the amount of re-oxygenation that had to be paid back to reach the half way recovery point. The half  $O_2$  debt is determined from the  $O_2\%$  at the point of release (handgrip failure) and not maximal de-oxygenation, as this may have occurred previously during the contraction (for examples see Figure 8.1 and Figure 8.2). Mean  $\pm$  SD suggest that in the FDP the  $O_2$  debt increased with ability group from control through to elite. Whereas in the FCR, the intermediate group had the smallest in  $O_2$  debt followed by the control, advanced and then elite groups. All ability groups had a smaller  $O_2$  debt in the FCR compared to their FDP. Statistical analyses were not performed on the half muscle  $O_2$  debt as this debt can be determined from the half recovery rise ·s (section 10.7.2),

and the time to half recovery (section 10.7.1). However, means  $\pm$  SD are reported in Table 10.6.

### **10.7 Half recovery characteristics**

The time taken to reach half recovery was calculated by subtracting the maximal de-oxygenation reached (e.g. de-oxygenated down to 48%) from the baseline oxygenation (e.g. 100%). The difference (52%) was then halved (26.5%) to determine the half recovery percentage. Therefore, the time (s) taken for the muscle re-oxygenation to recover to this amount (26.5%) was considered the time to half recovery.

Two, one-way between group MANOVA's were performed to investigate ability group differences in the time to half recovery characteristics in the FDP and the FCR post-sustained contraction. For the FDP and the FCR two dependent variables were used: time to half recovery, and half recovery saturation rise  $\cdot$ s. The independent variable was ability group. After both independent variables were log transformed there was a significant difference between ability groups on the combined dependent variables ( $F_{(6,38)} = 8.288, p < 0.0005$ ; Pillai's Trace 0.845). For the FCR the same log transformed dependent variables and the dependent variables were used as within the FDP. For the FCR there was also a significant difference between ability groups on the combined dependent variables ( $F_{(6,46)} = 2.555, p = 0.032$ ; Pillai's Trace 0.500). A series of one-way ANOVA's with post-hoc LSD were used to determine where the between groups differences lay.

#### **10.7.1 Time to half recovery**

As seen in Table 10.6 the mean  $\pm$  SD time taken (s) to reach half recovery within the FDP decreased from the control through to the elite group. Both the advanced and elite groups had a notably faster time to half recovery than the control and intermediate groups. Both the control and elite groups appear to of had a marginally faster time to half recovery in the FCR compared to the FDP. However, SD suggests this was much more varied amongst the control group. The speed of the time to half recovery within

the FCR decreased from the intermediate through to the elite groups as suggested in Table 10.6.

After a significant difference was seen in the one-way MANOVA, a series of one-way ANOVA's were used to explore potential differences in the time to half recovery (s) between the ability groups for the FDP and the FCR post-sustained contraction. For the FDP there was a significant difference between the ability groups ( $F_{(3,34)} = 22.575, p < 0.0005$ ) (after log transformation). The estimated variance explained by the mean effects within each group was 52%. Post-hoc LSD indicated the control group took significantly longer (s) to reach half recovery than the advanced (mean difference = 82.73, CI 39.62 – 125.84) and elite (mean difference = 86.27, 43.16 – 129.38) groups, but not the intermediate (mean difference = 48.05, CI 3.82 – 92.27). Furthermore, the intermediate group took significantly longer (s) than the advanced (mean difference = 34.68, CI 8.43 – 77.79) and elite (mean difference = 38.23, CI 4.88 – 81.34) groups. However, there was a non significant difference in the time to half recovery (s) between the advanced and elite (mean difference = 3.54, CI 38.42 – 45.5) groups. For the FCR there was a significant difference ( $F_{(3,33)} = 13.626, p < 0.0005$ ) between the ability groups (after the data was log transformed). The estimated variance explained by the mean effects within each group for the FCR was 31%. Post-hoc analyses revealed that unlike the FDP, the FCR in the control group did not recover significantly faster than the intermediate (mean difference = 48.66, CI 135.03 – 37.98), advanced (mean difference = 37.4, CI 49.24 – 124.04) or elite (mean difference = 64.58, CI 19.86 – 149.03) groups. However, the intermediate group took significantly longer to reach half recovery than both the advanced (mean difference = 86.06, CI 0.58 – 172.7) and elite (mean difference = 113.24, CI 28.8 – 197.69) groups.

#### ***10.7.2 Half recovery oxygen saturation rise per second***

Mean  $\pm$  SD in Table 10.6 suggests that during the time to half recovery, the per second re-oxygenation of the FDP was minimal in the control and intermediate groups whilst the advanced and elite groups had a much greater O<sub>2</sub>% rise ·s. Responses of the FCR were very similar to that of the FDP, with minimal gains in per second O<sub>2</sub>% for both the control and intermediate groups, and a notably larger per second gain in the advanced

and elite groups. In both the FDP and the FCR the elite group had the largest amount of  $O_2\%$  rise  $\cdot s$ .

After a significant difference was seen in the one-way MANOVA, a series of one-way ANOVA's were used to examine where differences in half recovery  $O_2\%$  rise  $\cdot s$  may lie. For the FDP muscle, the estimated variance explained by the mean effects within each group was 59%. After log transformation there was a significant difference, between the ability groups ( $F_{(3,34)} = 33.523$ ,  $p < 0.0005$ ). Post-hoc LSD indicated that the elite group had a significantly greater  $O_2\%$  rise  $\cdot s$  than the control (mean difference = 4.26, CI 2.38 – 6.14) and intermediate (mean difference = 3.83, CI 1.95 – 5.71) groups but not the advanced (mean difference = 1.64, CI 0.19 – 3.47). Furthermore, the advanced group had a significantly greater  $O_2\%$  rise  $\cdot s$  compared to the control (mean difference = 3.83, CI 0.74 – 4.50) and intermediate (mean difference = 1.64, CI 0.31 – 4.07) groups. For the FCR muscle, there was a non-significant difference ( $F_{(3,33)} = 2.234$ ,  $p = 0.234$ ) between the ability groups (after log transformation). The estimated variance explained by the mean effects was 41%. However, mean  $\pm$  SD in Table 10.6 suggests the elite group may have had a notably greater  $O_2$  rise  $\cdot s$  than the control (mean difference = 4.29, CI 1.35 – 7.23), intermediate (mean difference = 4.56, CI 1.62 – 7.5) and advanced (mean difference = 2.85, CI 0.95 – 5.79) groups. Furthermore, Table 10.6 suggests that the advanced group may have had a notably greater half  $O_2\%$  rise  $\cdot s$  than both the control (mean difference = 1.44, CI 1.57 – 4.46) and intermediate (mean difference = 1.71, CI 1.31 – 4.73) groups.

## **10.8 Intermittent contractions**

The following sections describe in detail the oxygenation characteristics of the FDP and the FCR muscles during the intermittent contractions and the subsequent recovery period. Furthermore, the sections go on to describe the characteristics of forearm BF (through the brachial artery) that occurred during the intermittent contractions (10s) and the release/rest (3s) periods.

### 10.8.1 Intermittent endurance characteristics

Similar to the sustained contraction (Table 10.2), mean  $\pm$  SD for the length of contraction during the intermittent test varied between ability groups with no meaningful trend (Table 10.7). However, mean  $\pm$  SD suggest the FTI grew as ability group increased from the control through to elite, with the exception of the advanced group who had a slightly lower FTI than the intermediate group.

**Table 10.7 Mean  $\pm$  SD group endurance characteristics of finger flexors during the intermittent contractions.**

	Control	Intermediate	Advanced	Elite
Length of contractions (s)	246 $\pm$ 131.84	331.84 $\pm$ 127.83	264 $\pm$ 59.51	365.2 $\pm$ 266.73
Force time integral (N x s)	25524 $\pm$ 16007*	33717 $\pm$ 7646*	31990 $\pm$ 11463*	53252 $\pm$ 29984

\*Shows the group is significantly different ( $p < 0.05$ ) from the elite group  
s = seconds, N x s = Newton's multiplied by seconds.

A one-way between groups MANOVA was performed to investigate ability group differences in the endurance characteristics during the intermittent contraction. Two dependent variables were used: length of contraction and the FTI. The independent variable was ability group. There was a significant difference between ability groups on the combined dependent variables ( $F_{(6,66)} = 3.183$ ,  $p = 0.008$ ; Pillai's Trace 0.449).

After a one-way MANOVA revealed there were significant differences between the groups for the combined independent variables, a series of one-way ANOVA's were used to determine where they may lay. For the length of contraction a one-way ANOVA revealed that there were no significant differences between the ability groups ( $F_{(3,36)} = 0.940$ ,  $p = 0.864$ ) (after log transformation). However, there was a significant difference between ability groups for the independent variable FTI ( $F_{(3,36)} = 3.853$ ,  $p = 0.036$ ), the estimated variance explained by the mean effect was 26%. Post-hoc LSD revealed that the elite group had a significantly higher FTI than the advanced (mean difference = 21261, CI 4249 – 38273), intermediate (mean difference = 19535, CI 2957 – 37012) and control (mean difference = 27727, CI 9684 – 457710) groups.

### 10.8.2 Contraction phase de-oxygenation

Section 10.10 provides an overview of the maximal de-oxygenation that occurred during the intermittent test. Based on previous work (MacLeod et al., 2007; Philippe et al., 2011), the amount of O<sub>2</sub> that was used during the contractions was defined and reported as the average of the first, middle and last three contraction phases. The same defined sets of first, middle and last phases were also used for the re-oxygenation data (section 10.9). Mean  $\pm$  SD in Table 10.8 and Table 10.9 presents the average de-oxygenation that occurred in the FDP and FCR during the first, middle and last three contractions during the intermittent test.

#### *Flexor digitorum profundus*

Table 10.8 suggests that during all three phases, the FDP became more de-oxygenated as climbing ability increased. Both the intermediate and advanced groups follow similar de-oxygenation profiles, a greater de-oxygenation was seen during the middle three contractions compared to the first and last three contractions. De-oxygenation within the elite and control groups appeared to decrease continually from the first through to the last three set of contractions. However, the elite group was able to reach a considerably lower point of de-oxygenation within the FDP muscle compared to the control group.

**Table 10.8 Mean  $\pm$  SD de-oxygenation (%) of the flexor digitorum profundus during the intermittent contractions.**

	First phase de-oxygenation (%)	Middle phase de-oxygenation (%)	Last phase O <sub>2</sub> de-oxygenation (%)
Control	7.8 $\pm$ 4.23	7.29 $\pm$ 3.46	6.08 $\pm$ 2.66
Intermediate	11.93 $\pm$ 4.19	8.78 $\pm$ 6.63	9.56 $\pm$ 2.63
Advanced	12.37 $\pm$ 5.46	10.37 $\pm$ 7.94	10.8 $\pm$ 6.34
Elite	15.73 $\pm$ 6.74	15.3 $\pm$ 7.33	11.45 $\pm$ 4.37

A one-way between groups MANOVA was performed to investigate ability group differences in the amount of de-oxygenation that took place in the FDP muscle during the first, middle and last three contraction phases of the intermittent test. Three dependent variables were used: de-oxygenation during the first, middle and last three contraction phases. The independent variable was ability group. There was a significant difference between ability groups on the combined dependent variables



( $F_{(9,99)} = 2.043$ ,  $p = 0.042$ ; Pillai's Trace 0.470). A series of one-way ANOVA's revealed that there were no significant between group differences in de-oxygenation during the first ( $F_{(3,36)} = 3.280$ ,  $p = 0.099$ ), middle ( $F_{(3,36)} = 3.005$ ,  $p = 0.132$ ) or last ( $F_{(3,36)} = 2.540$ ,  $p = 0.219$ ) sets of contractions. The estimated variance explained by the mean effects for the first, middle and last contraction phases were 23%, 21% and 18% respectively.

#### *Flexor carpi radialis*

Table 10.9 suggests that within the FCR, both the elite and advanced groups reached a notably lower point of de-oxygenation than the control and intermediate groups during the first phase of contractions. The elite group then followed a similar pattern as their FDP (Table 10.8), the amount of de-oxygenation reduced throughout the remainder of the test. De-oxygenation within the advanced group appeared to follow a similar pattern, decreasing less in the middle and last phases compared to the first. There appears to be almost no change in de-oxygenation within the control and intermediate groups throughout the three contraction phases.

**Table 10.9 Mean  $\pm$  SD de-oxygenation (%) of the flexor carpi radialis during the intermittent contractions.**

	First phase de-oxygenation (%)	Middle phase de-oxygenation (%)	Last phase de-oxygenation (%)
Control	8.33 $\pm$ 2.14	8.31 $\pm$ 2.88	8.21 $\pm$ 3.49
Intermediate	7 $\pm$ 3.33	6.41 $\pm$ 3.33	6.41 $\pm$ 4.13
Advanced	11.67 $\pm$ 6.38	7 $\pm$ 4.72	8.17 $\pm$ 4.6
Elite	13.32 $\pm$ 4.6	11 $\pm$ 5.49	9.1 $\pm$ 3.8

A one-way between groups MANOVA was performed to investigate ability group differences in the amount of de-oxygenation that took place in the FCR muscle during the first, middle and last contraction phases during the intermittent test. Three dependent variables were used: de-oxygenation during the first, middle and last three contraction phases. The independent variable was ability group. There was a non-significant difference between ability groups on the combined dependent variables ( $F_{(9,99)} = 1.373$ ,  $p = 0.211$ ; Pillai's Trace 0.333).

## 10.9 Rest phases during the intermittent contractions

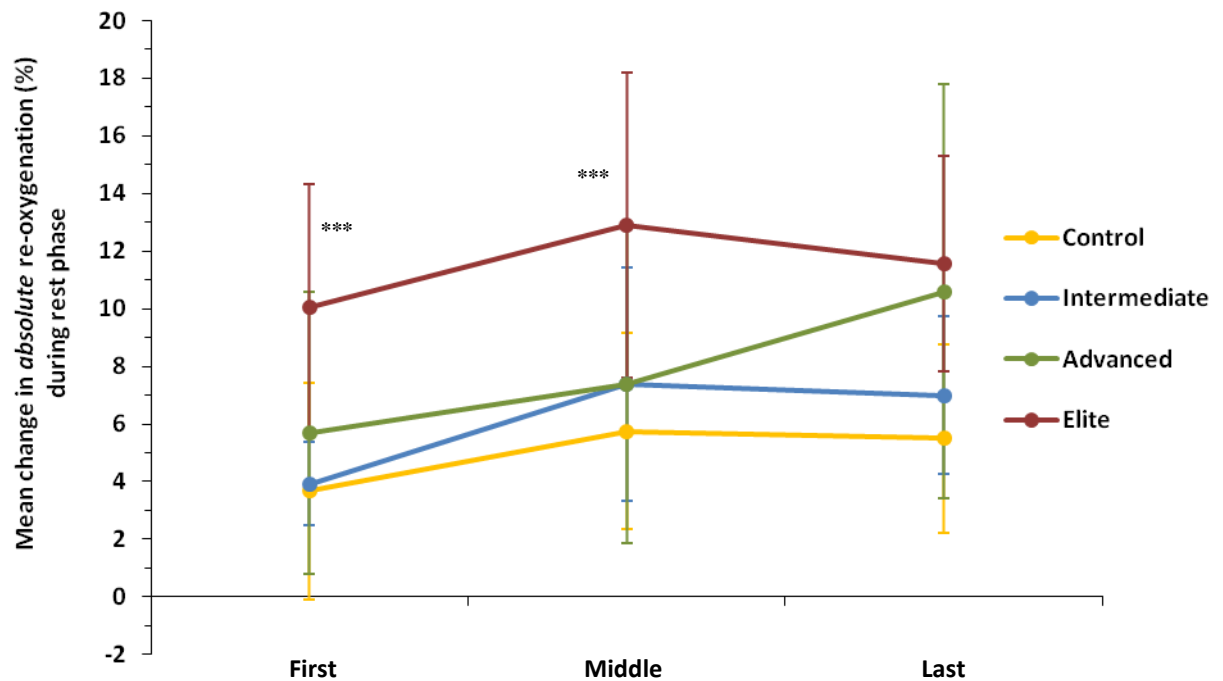
Section 10.9 describes the amount of de-oxygenation that occurred during the intermittent contraction phases, and the re-oxygenation that occurred during the intermittent rest phases. Data is presented as *relative* re-oxygenation  $\Delta$ , and *absolute* re-oxygenation  $\Delta$ . *Absolute* re-oxygenation  $\Delta$  is defined as the difference between the start of the 3s rest phase and the end of the 3s rest phase. *Relative* re-oxygenation  $\Delta$  is defined as the difference between the amount of O<sub>2</sub> used during the 10s contraction and the amount that is paid back during the 3s recovery.

### 10.9.1 Absolute rest phase re-oxygenation $\Delta$

#### *Flexor digitorum profundus*

Mean  $\pm$  SD in Figure 10.1 suggest that the control, intermediate and elite groups follow the same pattern during the three rest phases (first, middle and last). The groups show a rise in re-oxygenation during the first three contractions; this was followed by a further increase in re-oxygenation during the middle and last phases (here a plateau is seen). Although these groups show the same pattern, the re-oxygenation across the first, middle and last phases appeared to be considerably higher in the elites compared to all other ability groups. The recovery of the FDP within the advanced group appears to linearly increase throughout all rest phases, although re-oxygenation did not at any time point exceed values seen within the elite group.

A one-way between groups MANOVA was performed to investigate ability group differences in the *absolute* re-oxygenation  $\Delta$  that took place in the FDP during the first, middle and last three rest phases during the intermittent test. Three dependent variables were used: *absolute* re-oxygenation during the first, middle and last rest phases. The independent variable was ability group. There was a significant difference between ability groups on the combined dependent variables ( $F_{(9,99)} = 2.503$ ,  $p = 0.013$ ; Pillai's Trace 0.556).



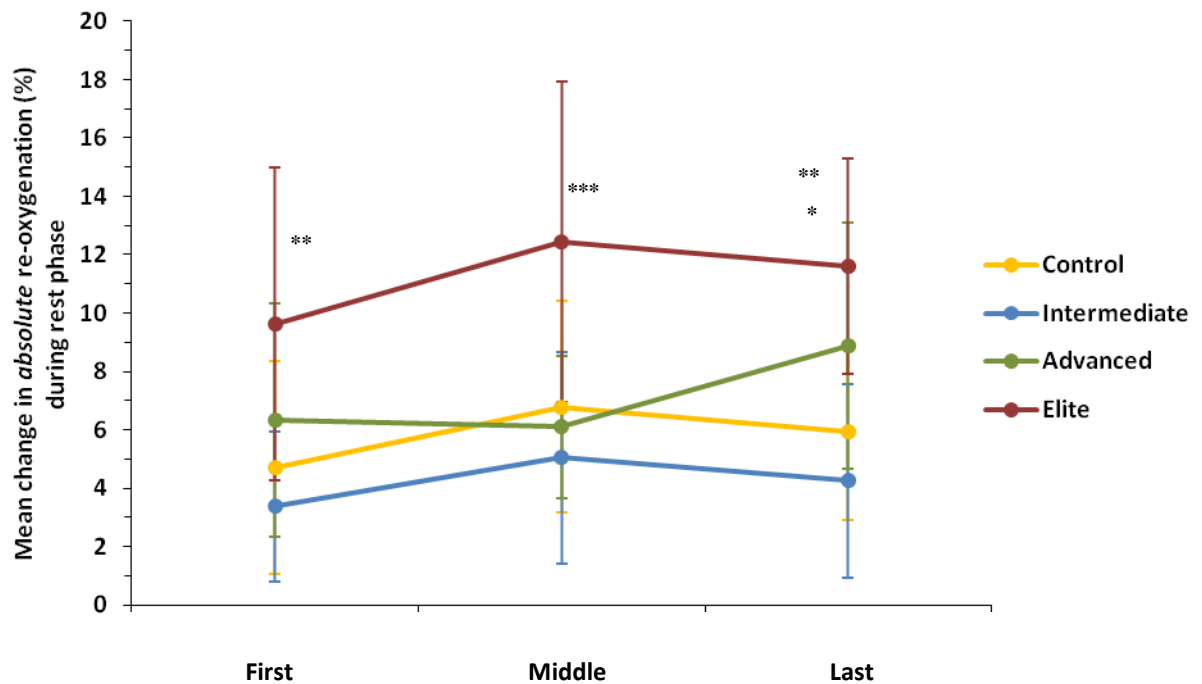
\*\*\* Shows significant difference ( $p < 0.05$ ) between the elite and all other groups  
 The values represent the difference between the start of the 3s rest phase and the end of the 3s rest phase.  
**Figure 10.1 Mean  $\pm$  SD *absolute* rest phase re-oxygenation ( $\Delta$ ) that occurred in the flexor digitorum profundus during the first, middle and last three phases of the intermittent test.**

After the significant MANOVA, a series of one-way ANOVA's were used to determine where the significant difference may have occurred. There was a significant difference in *absolute* re-oxygenation  $\Delta$  between ability groups during the first ( $F_{(3,36)} = 5.463, p = 0.012$ ) and middle ( $F_{(3,36)} = 4.159, p = 0.039$ ) phases, but not the last ( $F_{(3,36)} = 3.415, p = 0.087$ ); the estimated variance explained by the mean effects were 33%, 27% and 24% respectively. Post-hoc LSD suggested that during the first rest phase, the elite group had a greater *absolute* re-oxygenation in the FDP compared to the control (mean difference = 6.37, CI 2.63 – 10.1), intermediate (mean difference = 6.12, CI 2.49 – 9.73) and advanced (mean difference = 4.33, CI 0.81 – 7.86) groups. During the middle rest phase the elite group had a significantly greater *absolute* re-oxygenation  $\Delta$  in the FDP compared to the control (mean difference = 7.15, CI 2.59 – 11.71), intermediate (mean difference = 5.53, CI 1.11 – 9.95) and advanced (mean difference = 5.53, CI 1.24 – 9.83) groups.

### *Flexor carpi radialis*

Figure 10.2 suggests the FCR in the control, intermediate and elite groups had similar re-oxygenation profiles as within the FDP (Figure 10.1). Within the FCR the control and intermediate groups had small increases in *absolute* re-oxygenation  $\Delta$  across the first, middle and last rest phases. The advanced group had a similar response to both the control and intermediate groups, with relatively small increases in re-oxygenation. However, during the last rest phase, *absolute* re-oxygenation  $\Delta$  did appear to increase above the control and intermediate groups. The elite group had a notably greater *absolute* re-oxygenation  $\Delta$  during the first, middle and last three rest phases compared to all other groups, as with the FDP, a plateau was seen at the middle and last rest phases similar to the control and intermediate groups.

A one-way between groups MANOVA was performed to investigate ability group differences in the *absolute* re-oxygenation that took place in the FCR during the first, middle and last three rest phases. Three dependent variables were used: *absolute* re-oxygenation during the first, middle and last rest phases. The independent variable was ability group. There was a significant difference between ability groups on the combined dependent variables ( $F_{(9,96)} = 2.853$ ,  $p = 0.005$ ; Pillai's Trace 0.633).



\*\*\* Shows significant difference ( $p < 0.05$ ) between the elite and all other groups  
 \*\* Shows significant difference ( $p < 0.05$ ) between the elite, and the control and intermediate groups only  
 \* Shows significant difference ( $p < 0.05$ ) between the advanced and intermediate groups only  
 The values represent the difference between the start of the 3s rest phase and the end of the 3s rest phase.

**Figure 10.2 Mean  $\pm$  SD *absolute* rest phase re-oxygenation ( $\Delta$ ) that occurred in the flexor carpi radialis during the first, middle and last three rest phases of the intermittent test.**

After the significant MANOVA, a series of one-way ANOVA's were used to determine where the significant differences may have occurred. There was a significant difference in *absolute* re-oxygenation between ability groups during the first ( $F_{(3,35)} = 4.455, p = 0.03$ ), middle ( $F_{(3,35)} = 3.375, p = 0.048$ ), and the last ( $F_{(3,35)} = 7.072, p = 0.003$ ); the estimated variance explained by the mean effects were 30%, 24% and 40% respectively. Post-hoc LSD suggested that during the first rest phase, the elite group had a significantly greater *absolute* re-oxygenation  $\Delta$  in the FCR compared to the control (mean difference = 5.33, CI 1.29 – 9.37) and intermediate (mean difference = 6.67, CI 2.75 – 10.58), but not the advanced (mean difference = 3.7, CI 0.11 – 7.52) group. During the middle rest phase the elite group had a greater *absolute* re-oxygenation compared to the control (mean difference = 6.47, CI 0.45 – 12.48), intermediate (mean difference = 8.22, CI 2.39 – 14.06) and advanced (mean difference = 7.16, CI 1.47 – 12.85) groups. During the last rest phase, the elite group had a significantly greater *absolute* re-oxygenation compared to the control (mean

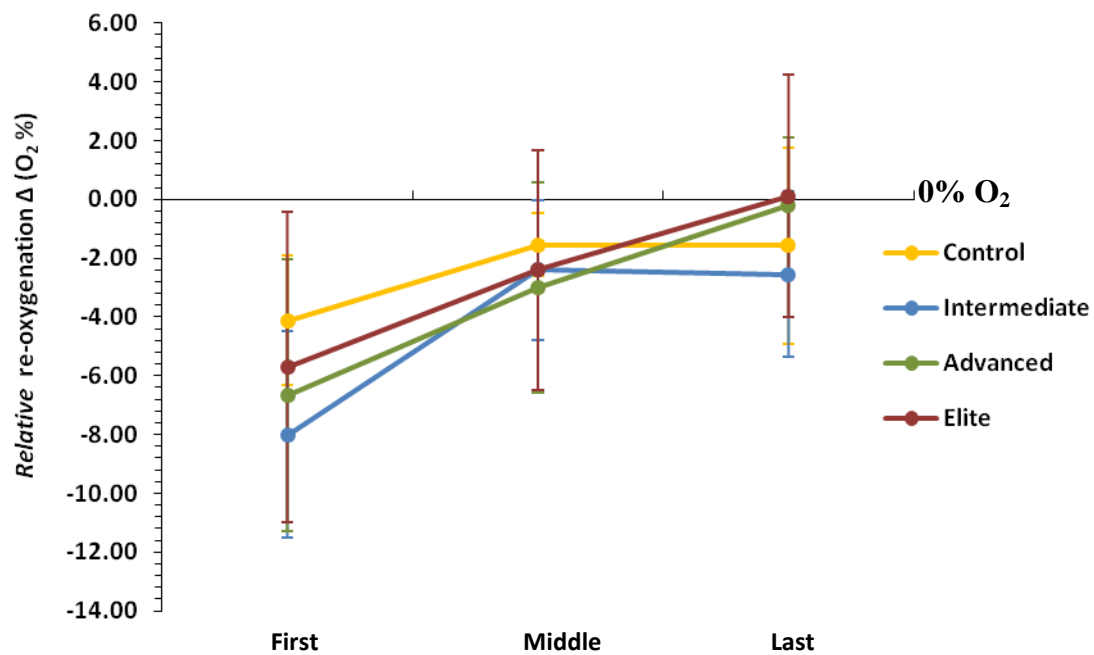
difference = 5.63, CI 2.03 – 9.23) and intermediate group (mean difference = 7.33, CI 3.84 – 10.83), but not the advanced (mean difference = 2.73, CI 0.68 – 6.13). Furthermore, during the last rest phase, the advanced group had a significantly greater absolute re-oxygenation compared to the intermediate (mean difference = 4.61, CI 1.2 – 8.01) group.

### ***10.9.2 Relative rest phase re-oxygenation $\Delta$***

Relative re-oxygenation considers the re-oxygenation during the 3s rest phases, with respect to the amount of de-oxygenation took place during the preceding contraction.

#### *Flexor digitorum profundus*

Mean  $\pm$  SD values shown in Figure 10.3 suggest that the FDP did not recover well during the first contraction phase in all ability groups. During the middle and last rest phases, the control and intermediate groups appeared to improve slightly. Both the control and intermediate groups had a plateau below zero O<sub>2</sub>% and did not fully recover back to the pre-contraction levels. Only for the advanced and elite groups did FDP re-oxygenation continue to improve throughout all three phases (first, middle, last). It was only during the last rest phase that the advanced and elite groups were able to re-oxygenate to the observed level before de-oxygenation occurred during the contraction phase.



The  $\Delta$  values represent the difference between the amount of  $O_2$  used during the 10s contraction and the amount that is re-saturated during the 3s recovery.

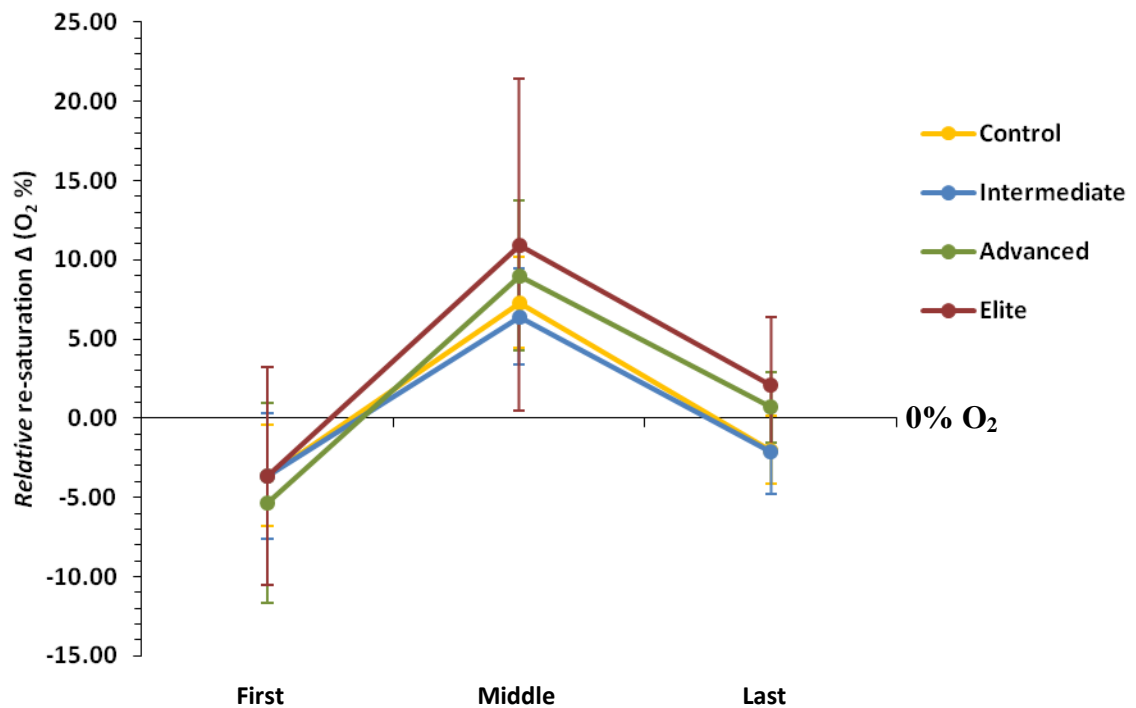
**Figure 10.3 Mean  $\pm$  SD *relative* rest phase re-oxygenation ( $\Delta$ ) that occurred in the flexor digitorum profundus during the first, middle and last three rest phases of the intermittent contractions.**

A one-way between groups MANOVA was performed to investigate ability group differences in the *relative* re-oxygenation  $\Delta$  that took place in the FDP during the first, middle and last contraction phases. Three dependent variables were used: *relative* re-oxygenation  $\Delta$  during the first, middle and last rest phases. The independent variable was ability group. There was a non-significant difference between ability groups on the combined dependent variables ( $F_{(9,99)} = 1.141$ ,  $p = 0.342$ ; Pillai's Trace 0.282).

#### *Flexor carpi radialis*

Figure 10.4 suggests that the FCR reacted to the intermittent contractions in a different manner to the FDP in all ability groups. In all groups the FCR was unable to fully recover to pre-contraction levels during the first phase of contractions. However, there was a marked improvement in re-oxygenation during the middle phase. In the middle phase, all groups recovered past the point of pre-contraction. Furthermore, the elite and advanced groups appeared to have had an even greater re-oxygenation than both the control and intermediate groups in this phase. During the last phase the control and intermediate groups did not recover back to pre-contraction levels, whereas, the elite

and advanced groups fully recovered, although not to the extent seen in the middle phase.



The  $\Delta$  values represent the difference between the amount of  $O_2$  used during the 10s contraction and the amount that is re-saturated during the 3s recovery.

**Figure 10.4 Mean  $\pm$  SD *relative* rest phase re-oxygenation ( $\Delta$ ) that occurred in the flexor carpi radialis during the first, middle and last three rest phases of the intermittent test.**

A one-way between groups MANOVA was performed to investigate ability group differences in the *relative* re-oxygenation  $\Delta$  that took place in the FCR during the first, middle and last three contraction phases. Three dependent variables were used: *relative* re-oxygenation  $\Delta$  during the first, middle and last rest phases. The independent variable was ability group. There was a non-significant difference between ability groups on the combined dependent variables ( $F_{(9,99)} = 1.717$ ,  $p = 0.096$ ; Pillai's Trace 0.416).



### 10.10 Maximal de-oxygenation characteristics

Maximal de-oxygenation describes the mean difference between the baseline level of oxygenation (rest) and the lowest O<sub>2</sub>% reached during the time course of the intermittent test. Mean  $\pm$  SD in Table 10.10 suggests that in the FDP, the maximal amount of de-oxygenation (%) was greater with an increase in climbing ability. However, this appears to not be the case for the FCR; here values remain relatively similar across all ability groups with the exception of the intermediate, group who appear to have a smaller  $\Delta$  de-oxygenation % compared to all other groups.

A one-way ANOVA was used to assess for potential differences in maximal  $\Delta$  de-oxygenation between ability groups. There was a significant difference between ability groups ( $F_{(3,36)} = 3.684$ ,  $p = 0.022$ ). For the FDP, the estimated variance explained by the mean effect was 25%. Post-hoc LSD revealed that in the FDP the elite group had a greater maximal  $\Delta$  de-oxygenation than both the intermediate (mean difference = 15.12, CI 1.1 – 29.96) and control (mean difference = 23.37, CI 8.46 – 38.29) groups, but not the advanced (mean difference 9.39, CI 4.66 – 23.45). For the FCR a one-way ANOVA revealed that there were no significant differences ( $F_{(3,36)} = 1.428$ ,  $p = 0.252$ ) in maximal  $\Delta$  de-oxygenation between any of the ability groups.

**Table 10.10 Mean  $\pm$  SD maximal de-oxygenation and re-oxygenation characteristics during and immediately post intermittent contractions in intermediate, advanced and elite climbers, as well as non-climbers.**

	$\Delta$ maximal de-oxygenation	Half O <sub>2</sub> % debt upon release	Time to half recovery s	Half O <sub>2</sub> % rise ·s
<b>FDP</b>				
Control	30.94 $\pm$ 13.21*	11.92 $\pm$ 6.21	92.5 $\pm$ 57.82	0.06 $\pm$ 0.03*,**
Intermediate	38.8 $\pm$ 8.33*	13.39 $\pm$ 4.89	81.78 $\pm$ 71.75	0.1 $\pm$ 0.06*,**
Advanced	44.92 $\pm$ 16.76	17.55 $\pm$ 6.26	14.4 $\pm$ 14.87****,***	1.12 $\pm$ 0.93
Elite	54.32 $\pm$ 19.93	19.83 $\pm$ 8.56	8.44 $\pm$ 3.71****,***	1.46 $\pm$ 0.79
<b>FCR</b>				
Control	34.84 $\pm$ 18.57	13.03 $\pm$ 7.58	76 $\pm$ 49.13	0.06 $\pm$ 0.02
Intermediate	21.11 $\pm$ 11.81	6.06 $\pm$ 2.37	49.5 $\pm$ 63.6	0.04 $\pm$ 0.03
Advanced	31.78 $\pm$ 16.74	9.04 $\pm$ 9.03	45.6 $\pm$ 83.89****	0.35 $\pm$ 0.56
Elite	33.3 $\pm$ 14.7	9.66 $\pm$ 9.09	15.5 $\pm$ 13.26****	0.49 $\pm$ 0.37

Half O<sub>2</sub> % debt upon release describes the amount of O<sub>2</sub> which needs to be paid back to return O<sub>2</sub> to baseline values. It is determined from the O<sub>2</sub>% at the point of release (handgrip failure) and not maximal de-oxygenation, as this may have occurred previously during the contraction (see Figure 8.1 and Figure 8.2).  $\Delta$  = delta score. FDP = flexor digitorum profundus, FCR = flexor carpi radialis.

\*Shows the group is significantly different ( $p < 0.05$ ) from the elite group

\*\*Shows the group is significantly different ( $p < 0.05$ ) from the advanced group

\*\*\*Shows the group is significantly different ( $p < 0.05$ ) from the intermediate group

\*\*\*\*Shows the group is significantly different ( $p < 0.05$ ) from the control group

### ***10.10.1 Half muscle oxygen debt***

Half muscle O<sub>2</sub> debt is the amount of re-oxygenation that had to take place to reach the half recovery point. The half O<sub>2</sub> debt is determined from the O<sub>2</sub>% at the point of release (handgrip failure) and not maximal de-oxygenation, as this may have occurred previously during the contraction (for examples see Figure 8.1 and Figure 8.2). Table 10.10 suggests that in the FDP, half of the O<sub>2</sub> debt created during the contraction increased with ability group from control through to elite. The greater the climbing ability group the greater the amount of O<sub>2</sub> debt which had to be re-oxygenated within the FDP. Although to a lesser extent, it was the same trend within the FCR, except for the control group who appeared to have had the greatest half muscle O<sub>2</sub> debt. Statistical analyses were not performed on the half muscle O<sub>2</sub> debt during recovery after the intermittent contractions, as this can be determined from the half recovery rise (section 10.7.2) and the time to half recovery (section 10.7.1). However means  $\pm$  SD are presented in Table 10.10.

### ***10.11 Half recovery characteristics***

Time to half recovery post-intermittent contractions was determined in the same way as it was for the sustained recovery. This is described in detail in section 10.7. Two, one-way between group MANOVA's were performed to investigate ability group differences in time to half recovery characteristics in the FDP and the FCR. For the FDP two dependent variables were used: time to half recovery, and oxygenation rise (half recovery). The independent variable was ability group. There was a significant difference between ability groups on the combined dependent variables ( $F_{(6,46)} = 4.315, p = 0.002$ ; Pillai's Trace 0.720). A series of one-way ANOVA's with post-hoc LSD were used to determine where the between groups differences may lay (sections 10.11.1 and 10.11.2). For the FCR there was a significant difference between ability groups on the combined dependent variables ( $F_{(6,46)} = 2.555, p = 0.032$ ; Pillai's Trace 0.500).

### **10.11.1 Time to half recovery**

The time taken to reach half recovery in the FDP not only took longer in the control and intermediate groups compared to the advanced and elite, but the SD's were also much larger. Within the FCR the control group took the longest time to get to the half recovery point and the elite group the shortest. The intermediate group took less time than the control, but this was similar to the advanced group. The advanced and elite groups took longer to recover in the FCR than the FDP, whereas the control and intermediate groups appeared to have a faster recovery within the FCR.

After a significant MANOVA (section 10.11) was reported, a series of one-way ANOVA's were used to explore potential differences in the time to half recovery (s) between the ability groups for the FDP and the FCR post-intermittent contraction. For the FDP there was a significant difference ( $F_{(3,27)} = 10.852, p < 0.0005$ ) between ability groups (after log transformation). The estimated variance explained by the mean effects for the FDP was 35%. Post-hoc LSD indicated that the control group took significantly longer (s) to reach half recovery than the advanced (mean difference = 62.97, CI 27.22 – 98.72) and elite (mean difference = 62, 27.91 – 96) groups, but not the intermediate (mean difference = 6.27, CI 43.232 – 30.7) group. Furthermore, the intermediate group took significantly longer (s) to recover than the advanced (mean difference = 69.24, CI 35.28 – 103.2) and elite groups (mean difference = 68.22, CI 36.04 – 100.4). For the FCR there was a significant difference between the ability groups ( $F_{(3,26)} = 4.263, p = 0.032$ ). The estimated variance explained by the mean effects within each group was 20%. Post-hoc analyses revealed the control group took significantly longer to recover than the advanced (mean difference = 49.17, CI 15.68 – 82.66) and elite (mean difference = 53.17, CI 19.68 – 86.66) groups.

### **10.11.2 Half recovery oxygenation rise per second**

Table 10.10 suggests marked differences between ability groups in mean  $\pm$  SD oxygenation rise  $\cdot$ s for the FDP. Although the advanced group have a slightly smaller O<sub>2</sub>% recovery per second than the elite group, both are considerably greater than the amount of per second recovery seen within the intermediate and control groups. Within the FCR, control and intermediate groups showed a similar response as was seen in the FDP, only a very small O<sub>2</sub>% rise  $\cdot$ s. The elite and advanced groups also had the same

trend as the FDP, except the amount re-oxygenation per second in each of the groups was smaller than those seen within the FDP.

After a significant MANOVA (section 10.11) was reported, a series of one-way ANOVA's were used to examine possible differences in the oxygenation rise per second for half recovery between the ability groups in both the FDP and the FCR. For the FDP there was a significant difference, between the ability groups ( $F_{(3,26)} = 7.777, p = 0.002$ ). The estimated variance explained by the mean effects within each group was 27%. Post-hoc LSD indicated that the elite group had a significantly greater oxygenation rise  $\cdot$ s than the control (mean difference = 1.4, CI 0.63 – 2.17) and intermediate (mean difference = 1.37, CI 0.64 – 2.09) groups, but not the advanced (mean difference = 0.34, CI -0.35 – 1.04). Furthermore, the advanced group had a significantly greater oxygenation rise  $\cdot$ s compared to the control (mean difference = 1.06, CI 1.06 – 0.39) and intermediate (mean difference = 1.02, CI 1.02 – 0.37) groups. For the FCR muscle there was a non-significant difference between the ability groups ( $F_{(3,26)} = 2.443, p = 0.180$ ).

### **10.12 Intermittent forearm blood flow characteristics**

Baseline BF characteristics are reported in section 10.4. In order to assess ability group differences in forearm BF characteristics during the intermittent contractions, measurements are reported during the 10s contractions and during the 3s release. Furthermore, the mean change ( $\Delta$ ) was determined for the velocity, BF and HR. Mean change was calculated by finding the difference between the release and contraction values for velocity, BF and HR.

#### **10.12.1 Velocity characteristics**

Velocities measured during the contraction periods appear to have no distinguishable trend between ability groups. However, it is clear that the elite group had a higher average velocity than all other ability groups. During the 3s release periods the elite group appeared to of had a much greater release velocity than all other groups. Table 10.11 suggests that as ability group increases so does the  $\Delta$  blood velocity.

**Table 10.11 Mean  $\pm$  SD for velocity responses during the intermittent contraction and release periods, as well as the  $\Delta$  scores.**

	Control	Intermediate	Advanced	Elite	<i>F</i> value df 3,37	<i>p</i> value
Contraction velocity (mm · s)	41.16 $\pm$ 12.73	36.73 $\pm$ 22.67	30.19 $\pm$ 4.48	49.28 $\pm$ 17.05	3.068	0.639
Release velocity (mm · s)	79.91 $\pm$ 22.33	80.61 $\pm$ 19.66	78.68 $\pm$ 15.32	100.82 $\pm$ 8.96	3.826	0.756
$\Delta$ velocity (mm · s)	38.75 $\pm$ 19.6	43.88 $\pm$ 24.05	49.4 $\pm$ 15.59	53.93 $\pm$ 16.37	1.243	0.297

*$\Delta$  Velocity represents the difference between release and contraction values*

A one-way between groups MANOVA was performed to investigate ability group differences in velocity characteristics through the brachial artery during the intermittent contractions. Three dependent variables were used: contraction velocity, release velocity and  $\Delta$  velocity (defined in section 10.12). The independent variable was ability group. There was a non-significant difference between ability groups on the combined dependent variables ( $F_{(9,102)} = 1.862$ ,  $p = 0.066$ ; Pillai's Trace 0.432).

Although the one-way MANOVA revealed no significant differences between ability groups, the mean difference and CI revealed interesting trends in the release velocity, and the  $\Delta$  velocities. During the release, the elite group had a notably greater velocity than the control (mean difference = 20.9, CI 5.41 – 36.39), intermediate (mean difference = 20.2, CI 3.14 – 37.28) and advanced (mean difference = 22.14, CI 7 – 37.27) groups. Lastly, the mean difference between contraction and release showed that  $\Delta$  velocity increased with ability group. The elite mean  $\pm$  SD velocity appears to be greater than the control (mean difference = 15.18, CI 1.73 – 32.1), intermediate (mean difference = 10.05, CI 8.58 – 28.69) and advanced (mean difference = 4.53, CI 11.99 – 21.06) groups.

### **10.12.2 Forearm blood flow**

With the exception of the elite group having a higher BF during the contraction compared to all other groups, there appears to have been no particular trends or differences between ability groups. Blood flow during the release of contraction increased as ability group increased, with the elite group having a notably higher BF

than all other groups. Furthermore,  $\Delta$  forearm BF suggests there may be an increase in BF with an increase in climbing ability.

**Table 10.12 Mean  $\pm$  SD for blood flow responses during the intermittent contraction and release periods, as well as the  $\Delta$  scores.**

	Control	Intermediate	Advanced	Elite	<i>F</i> value df 3,32	<i>p</i> value
Contraction BF (mL·min <sup>-1</sup> )	366 $\pm$ 150	346 $\pm$ 297	284 $\pm$ 76	462 $\pm$ 228	1.124	0.312
Release BF (mL·min <sup>-1</sup> )	656 $\pm$ 239	701 $\pm$ 231	764 $\pm$ 230	971 $\pm$ 152	3.076	0.723
$\Delta$ BF (mL·min <sup>-1</sup> )	289 $\pm$ 140	355 $\pm$ 194	480 $\pm$ 198	494 $\pm$ 235	2.567	0.591

*BF = blood flow,  $\Delta$  BF represents the difference between release and contraction values*

A one-way between groups MANOVA was performed to investigate ability group differences in BF characteristics through the brachial artery during the intermittent contractions. Three dependent variables were used: contraction BF, release BF and  $\Delta$  BF. The independent variable was ability group. There was a non-significant difference between ability groups on the combined dependent variables ( $F_{(9,87)} = 1.635$ ,  $p = 0.118$ ; Pillai's Trace 0.434).

A one-way MANOVA suggested there were no-significant differences between ability groups on the combined dependent variables. However, mean difference and CI suggest that the elite group may have had a notably greater release value and  $\Delta$  BF. For the release contraction the elite group had a notably higher BF than the control (mean difference = 315, CI 94 – 536), intermediate (mean difference = 269, CI 30 – 509) and advanced (mean difference = 207, CI 18 – 433) groups. For  $\Delta$  BF, the elite group were notably greater than the control (mean difference = 205, CI 13.6 – 397) and intermediate (mean difference = 139, CI 68 – 346) groups, but were only marginally greater than the advanced group (mean difference = 14, CI 181 – 210).

### 10.12.3 Heart rate responses

Data shown in Table 10.13 suggests that with the exception of the intermediate group, HR during the intermittent contractions remained relatively similar across all ability groups. Table 10.13 suggests that during the 3s rest period the HR became elevated above that seen during the contraction. Furthermore, the elite group had a notably greater release HR than all other groups. As ability group increased there was a concurrent increase in the  $\Delta$  HR values. The elite group had a notably higher  $\Delta$  HR compared to all other groups.

**Table 10.13 Mean  $\pm$  SD heart rate responses during intermittent contractions and release periods, as well as the  $\Delta$  scores.**

	Control	Intermediate	Advanced	Elite	<i>F</i> value df 3,36	<i>p</i> value
Contraction HR (bts·min <sup>-1</sup> )	88 $\pm$ 18	69 $\pm$ 6	86 $\pm$ 14	85 $\pm$ 10	3.366	0.09
Release HR (bts·min <sup>-1</sup> )	94 $\pm$ 15*	80 $\pm$ 9*	98 $\pm$ 16*	110 $\pm$ 11	7.099	0.003
$\Delta$ HR (bts·min <sup>-1</sup> )	5 $\pm$ 9*	11 $\pm$ 7*,**	12 $\pm$ 4*	25 $\pm$ 8	12.817	< 0.0005

*HR = heart rate,  $\Delta$  HR represents the difference between release and contraction values*

\*Shows the group is significantly different ( $p < 0.05$ ) from the elite group

\*\*Shows the group is significantly different ( $p < 0.05$ ) from the advanced group

A one-way between groups MANOVA was performed to investigate ability group differences in HR responses measured in the brachial artery during the intermittent contractions. Three dependent variables were used: contraction HR, release HR and  $\Delta$  HR. The independent variable was ability group. There was a significant difference between ability groups on the combined dependent variables ( $F_{(6,66)} = 7.279$ ,  $p < 0.0005$ ; Pillai's Trace 0.796).

After the one-way MANOVA revealed significant differences between ability groups on the combined dependent variables, a series of one-way ANOVA's were conducted on each dependent variable. After Bonferoni adjustment there was a non-significant difference in contraction HR between the ability groups ( $F_{(3,36)} = 3.366$ ,  $p = 0.09$ ). The estimated variance explained by the mean effects within each group for the contraction HR was 23%.

Table 10.13 shows that there was a significant difference between ability groups for both the release HR ( $F_{(3,36)} = 7.099, p = 0.003$ ), and the  $\Delta$  HR ( $F_{(3,36)} = 12.817, p < 0.0005$ ), the estimated variance explained by the mean effects were 39% and 54% respectively. For release HR post-hoc analyses revealed that the elite group had a significantly higher HR upon release than the intermediate (mean difference = 30, CI 17 - 43) and control (mean difference = 17, CI 4 - 29) groups, but not the advanced (mean difference = 13, CI 0.8 - 25). Furthermore, the advanced group had a significantly higher release HR than the intermediate group (mean difference = 17, CI 4 - 30). For the  $\Delta$  HR post-hoc analyses revealed that elite group had a significantly higher  $\Delta$  HR than the control (mean difference = 20, CI 13 - 26), intermediate (mean difference = 14, CI 6 - 21) and advanced (mean difference = 13, CI 6 - 19) groups.



## Discussion for Study Two

Only three known studies have investigated the haemodynamic responses in rock climbers (Ferguson & Brown, 1997; MacLeod et al., 2007; Philippe et al., 2011), of which two assessed oxygenation changes (MacLeod et al., 2007; Philippe et al., 2011), and one assessed BF and blood pressure recovery characteristics (Ferguson & Brown, 1997). However, these studies focused solely on intermediate (defined as best on-sight of 24 Ewbank) (MacLeod et al., 2007) and elite (Philippe et al., 2011) rock climbers (World Cup competitors), assessing oxygenation in the FDS or the FDP respectively. No known study has simultaneously assessed tissue oxygenation within two forearm flexor muscles in multiple ability groups of rock climbers. More importantly, no known study has assessed de-oxygenation and re-oxygenation characteristics during sustained or intermittent contractions, as well as throughout the subsequent post-exercise recovery period. Therefore, the purpose of this study was to assess de-oxygenation and re-oxygenation, as well as BF characteristics in intermediate, advanced and elite climbers, as well as a control group, during and immediately post-exercise (sustained and intermittent contractions-to-failure). The major findings of this study were: 1) maximal de-oxygenation of the FDP and FCR is significantly greater in elite and advanced rock climbers compared to intermediate climbers and a control group, 2) during intermittent contractions to failure, *relative* re-oxygenation is an important determinant of the FTI in multiple ability groups of rock climbers, 3) increases in  $\Delta$  BF, release HR and  $\Delta$  HR suggest that vessel occlusion may not be as prominent in advanced and elite climbers as previously thought, and 4) time to half recovery post-cessation of exercise was significantly faster in elite and advanced climbers compared to all other lower ability groups, even though they reached a significantly lower saturation point during the contractions.

Philippe et al. (2011) reported no gender differences in the re-oxygenation characteristics of World Cup rock climbers. However, previous studies investigating strength related aspects of performance, such as time-to-failure and MVC in forearm trained and untrained populations, have suggested between gender differences (Hunter, 2009; Hunter & Enoka, 2001; Hunter, Griffith, Schlachter, & Kufahl, 2009). Therefore, study two only recruited male participants ( $n = 44$ ). As previously mentioned in Chapter 9, six individuals were removed due to technical errors with the NIRS or ultra sound

equipment. The remaining 38 males comprised a control ( $n = 9$ ), intermediate ( $n = 9$ ), advanced ( $n = 10$ ) and elite ( $n = 10$ ) groups. Climbers were chosen based on the same self-report criteria used within study one, Chapter 5 (see Appendix H for validation study).

### **11.1 Demographic and anthropometric data**

The anthropometric and demographic characteristics of the participants are presented within Table 9.1. The IPAQ was used to quantify the general amount of exercise that was conducted by the participants within each group. This was deemed important for the current study as the control group needed to be non-forearm trained, but were required to be active and not sedentary. There were no significant differences between groups for any of the responses to the seven questions and mean  $\pm$  SD in Table 8.1 suggest no notable trends within the data. Data suggests that any differences between groups presented in chapter 8 are not due to differences in generalised physical activity or fitness, but a more climbing specific fitness.

As would be expected, there were minimal differences in the anthropometric characteristics between the control and intermediate groups. However, body weight and body fat percentage for the control and intermediate groups was significantly higher than for the advanced and elite groups. These significant differences in body composition are unsurprising, as although the physical activity levels were similar between all groups (Table 9.1), previous anthropometric data on rock climbers suggests low body fat percentage and weight are common attributes for high ability sport climbers (Cheung et al., 2011; España-Romero et al., 2006; Watts et al., 1993a). Furthermore, the elite group had a significantly higher years climbing experience, sessions climbing per week and hours climbing per week compared to the advanced and intermediate groups suggesting a high level of climbing specific training. The elite climbers had a similarly low body fat percentage and weight compared to the elite climbers reported by Philippe et al. (2011), although climbers in the present study were of a slightly lower ability (-3 grades Ewbank). The intermediate group had a higher body fat percentage than those reported by MacLeod et al. (2007). However the intermediate participants described by MacLeod et al. (2007) had a best on-sight grade of 24 (Ewbank) which represents more of an advanced climber rather than an

intermediate (based on a pilot study (Appendix G) and previous literature (Draper et al., 2009)).

### **11.2 Maximal volitional contraction and strength-to-weight ratio**

Study two is one of only a few which measured MVC using a sport specific climbing ergometer (Grant et al., 2003; López-Rivera & González-Badillo, 2012; MacLeod et al., 2007; Philippe et al., 2011; Schweizer & Furrer, 2007). Table 10.2 suggests that unlike previous studies, there were not only significant differences in MVC between groups, but there was a continually increasing trend with the concurrent increase in ability level. The elite group had a significantly higher MVC compared to both the intermediate climbers and the control group, mean differences were 167.4 (N) and 138.95 (N) respectively. This contradicts previous studies (Ferguson & Brown, 1997; Grant et al., 1996) which revealed no differences in MVC between ability groups. However, as previously mentioned (section 3.6), these studies used HGD and not a sport specific handgrip apparatus. Recent studies using sport specific apparatus also found significant differences between climbers and non-climbers (MacLeod et al., 2007; Philippe et al., 2011; Vigouroux, Quaine, Labarre-Vila, & Moutet, 2006). MacLeod et al. (2007) suggested that MVC explained 49.9% of the variability in on-sight climbing grade. However, it should be noted that MacLeod et al. (2007) used a very homogenous group of climbers.

Data from study two builds upon evidence suggesting MVC obtained using a sport specific ergometer can be used as a sensitive measure of rock climbing performance. Nonetheless, it has been suggested that strength-to-weight ratio may be superior indicator (Mermier et al., 2000; Philippe et al., 2011; Watts et al., 2003). Study two supports this notion; the estimated variance explained by strength-to-weight ratio was 49%, (versus 36% for MVC). Table 10.2 suggests that with the concurrent increase in ability level from control to elite, there was an increase in strength-to-weight ratio. Not only did elite climbers have a significantly greater strength-to-weight ratio than non-climbers (similar to (MacLeod et al., 2007; Philippe et al., 2011; Quaine et al., 2003; Vigouroux et al., 2006)), they were significantly greater than all lesser ability climbing groups (Table 10.2). Regression analysis was not performed as the ability groups were extremely homogenous with regards to best performance grade (on-sight). However, as

strength-to-weight ratio increased with the best self-reported on-sight grade, data from study two suggests that training which would improve sport specific MVC may notably increase rock climbing performance.

Although forearm girth was not measured in study two, España-Romero and Watts (2012) found that finger flexor strength was significantly greater in climbers compared to non-climbers, yet there were no differences in forearm volume when measured using water displacement. In part, findings from the current study support the conclusion of España-Romero and Watts (2012) that neural factors or an increase in capillary density, and not hypertrophy may account for the strength differences between climbers and non-climbers. Table 10.8, Table 10.9, Figure 10.3 and Figure 10.4 suggest that de-oxygenation and re-oxygenation (particularly when considered as a relative value), as well as capillary density may also help to explain strength and endurance differences between a variety of different ability climbers and non-climbers.

### **11.3 Climbing specific finger endurance**

As previously mentioned, Ferguson and Brown (1997) were the first known authors to report contraction times during intermittent contractions to failure. The authors used a contraction relaxation cycle of 5s – 2s at 40% of MVC. Endurance time-to-failure surpassed twelve minutes in climbers, and consequently either the ratio or percentage of MVC did not represent the average ascent time for a standard indoor World Cup competition route (Schadle-Schardt, 1998). Both MacLeod et al. (2007) and Philippe et al. (2011) used the contraction relaxation ratio of 10s – 3s, and consequently the time-to-failure was far more representative of indoor competition routes. Table 10.3 and Table 10.7 suggest the length-of-contractions in study two were similar to competition route duration, as well as other studies which investigated the physiological responses to rope climbing (Draper et al., 2008; España-Romero et al., 2012; Schadle-Schardt, 1998; Watts & Drobish, 1998).

Mean  $\pm$  SD within Table 10.3 and Table 10.7 suggest that for time-to-failure during the sustained and intermittent contractions, there were no significant differences or meaningful trends between any of the ability groups. Previous studies which have assessed endurance times in non-climbers have found a shorter isometric endurance

with those who had a greater MVC (Carlson & McCraw, 1971; Carlson, 1969; Ferguson & Brown, 1997). However, studies which have accurately assessed more sport specific finger flexor endurance in climbers have shown that there were no differences in endurance times between climbers and non-climbers during a sustained test regardless of their MVC (Ferguson & Brown, 1997; Grant et al., 2003; MacLeod et al., 2007). However, it should be noted that MVC measures strength, and is not necessarily related to endurance performance. The absence of this negative relationship between MVC and endurance is more likely caused by the elite group being able to contract for a longer period of time as opposed to the lower level groups contracting for a shorter period of time. Although previous studies have suggested that this relationship is the other way around in climbers, as BF may be occluded in more advanced performers, these studies either did not measure BF during the contraction (Ferguson & Brown, 1997) or did not measure it at all (MacLeod et al., 2007). Data from study two suggests that although non-significant,  $\Delta$  BF during the last minute of sustained contraction maybe elevated in elite and advanced climbers compared to control and intermediate groups. However, this is at the conduit level, and the elite climbers are likely to have a greater capillarisation, and therefore a greater capacity to directly perfuse or activate cells, as data within Table 10.6 and Table 10.10 suggests. It may be that the ability of the elite and advanced climbers to maintain contraction at 40% MVC and oppose BF occlusion, could be due to an increase in the metaboreflex. The metaboreflex consists of heightened cardiac output, stroke volume, pressor response and HR (O'Leary, 1993). This would allow for a greater perfusion pressure or increased vascular conductance, therefore improving the capacity to deliver BF during contractions. Although study two did not measure the pressor response, vascular conductance, cardiac output or stroke volume, Table 10.5 suggests the metaboreflex may be present, as with an increase in ability there is an increasing trend in velocity, forearm BF and HR measured in the brachial artery. Although this artery reflects total forearm BF and not that solely in the FDP and FCR, the increase in BF may still suggest a stronger presence of the metaboreflex in advanced and elite rock climbers. However, as the current study did not measure all variables associated with the metaboreflex, and revealed no significant differences in forearm BF or HR (just a large increasing trend) during the sustained contraction, then this heightened presence are merely a speculative one.

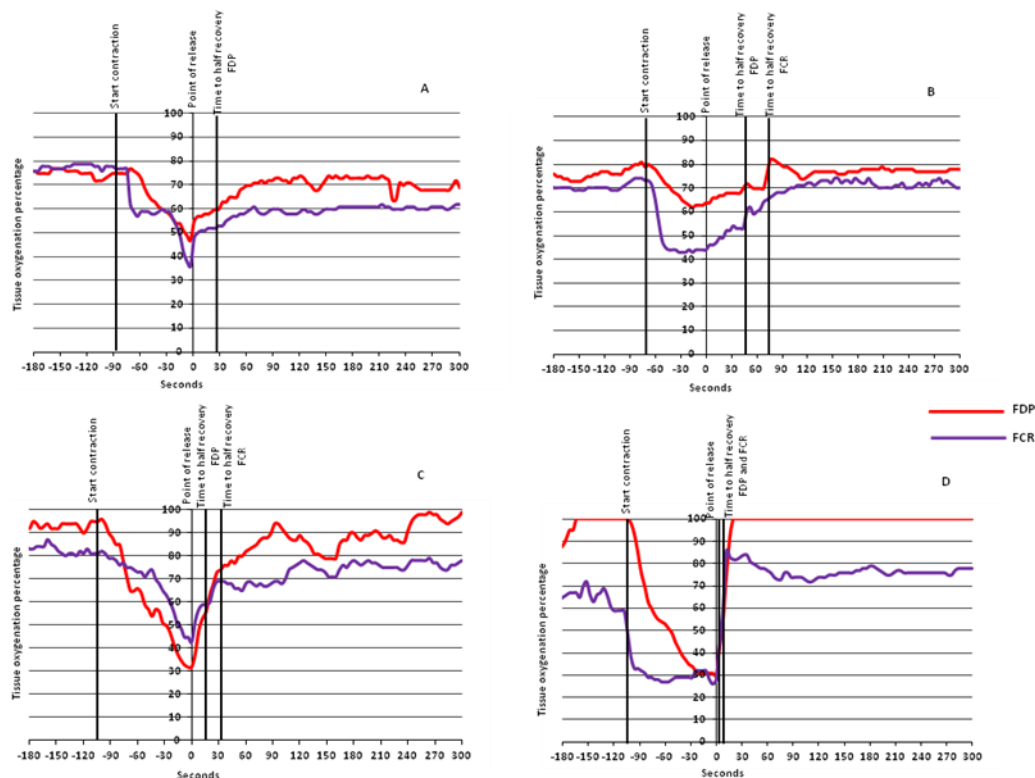
#### **11.4 Determinants of the force time integral**

The FTI is deemed an excellent sport specific measure of performance for rock climbers as it encompasses both MVC and time-to-failure. Previous studies have shown a significantly greater FTI during intermittent contractions in climbers with a best on-sight ability of greater than grade 24 (Ewbank) (MacLeod et al., 2007; Philippe et al., 2011). However, for a sustained contraction the FTI appears to be only significantly greater in exceptionally high level climbers (World Cup) (Philippe et al., 2011).

##### **11.4.1 Sustained contraction**

Figure 11.1 presents an example of a NIRS trace for a control, intermediate, advanced and elite climber during baseline measurement, the sustained contraction and the subsequent five-minute recovery period. As soon as the contraction began there was a decline in tissue oxygenation, this was significantly faster in the elite climbing group within the FDP and FCR (Table 10.6). Like previous maximal effort studies, this decline tended to level off near to the point of failure suggesting that the muscle had reached its maximal capacity for extracting O<sub>2</sub> from the perfusing blood (Pereira et al., 2007). The small SD seen in the elite group, suggest that they are close to the human physical limit for perfusing O<sub>2</sub> from the muscle

Data from study two revealed that for the sustained contraction there were no significant differences in the FTI, as well as no notable trends between any of the ability groups. It was expected that the FTI would have been greater in the elite climbers compared to all other groups. As previously mentioned this may be due to the longer than expected length-of-contraction seen in the elite and advanced groups. The increasing trend in BF and HR may have suggested either less occlusion or a greater perfusion pressure to a degree, but these may not have been great enough to significantly increase the FTI as previously seen in World Cup climbers (Philippe et al., 2011).



**Figure 11.1** Example near infrared spectroscopy traces for control (A), intermediate (B), advanced (C) and elite (D) participants during the baseline, *sustained* contraction and passive recovery.

This study suggests that BF and HR had an increasing trend with the concurrent increase in ability, a finding in line with the slightly elevated pressor response reported by MacLeod et al. (2007). It is possible that these increases may oppose occlusion enough to increase the length-of-contraction in the elite climbers, but were not enough to make the FTI significantly greater. Although Philippe et al. (2011) did not measure the pressor response, BF or HR responses in World Cup climbers, the authors did report a significantly higher FTI in elite World Cup climbers during the sustained contraction. As no such difference occurred within study two, more research is required with a greater number of higher level athletes to determine why differences in FTI of World Cup athletes may occur, and if these factors are trainable ones. It may be that the increasing trends in the haemodynamic responses seen in study two could be exacerbated in higher level athletes, and may be responsible for the difference between study two and the FTI previously seen in World Cup athletes.

#### 11.4.2 Intermittent contraction

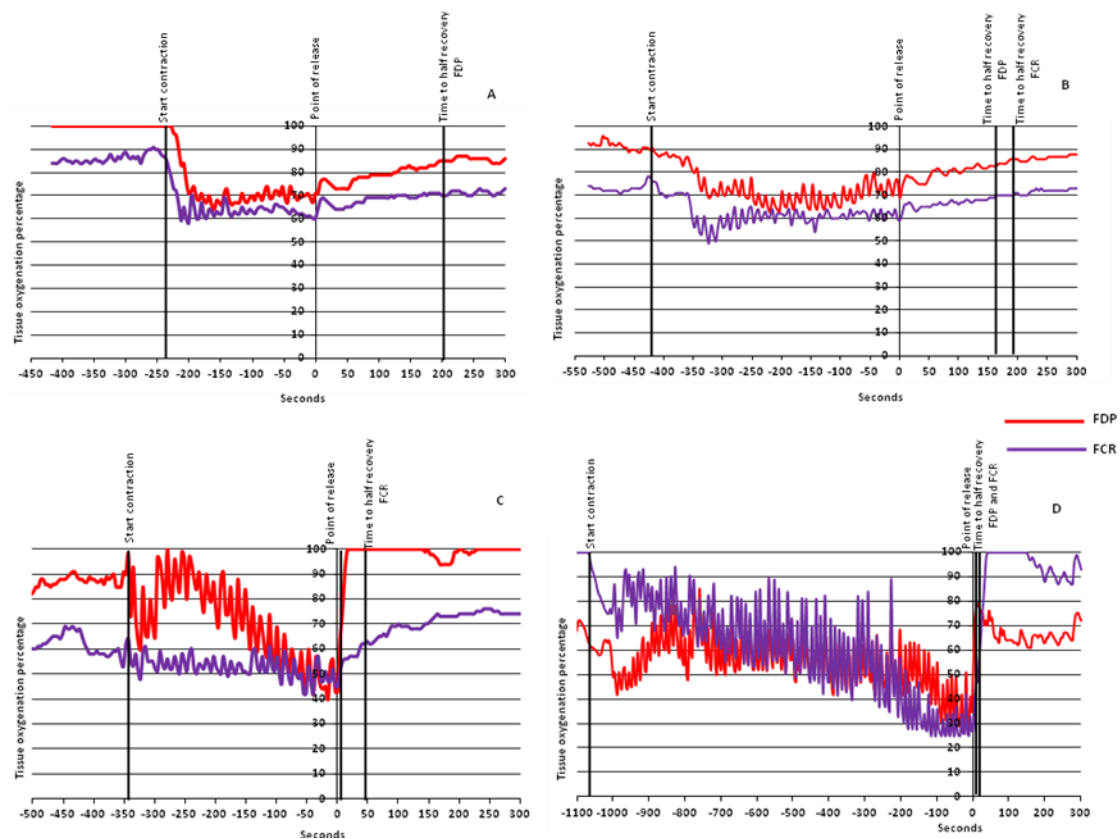
Data within Table 10.7 suggests that during the intermittent test the elite group had a significantly higher FTI compared to all other groups. Although MacLeod et al. (2007) showed that climbers who had a best on-sight grade of 24 (Ewbank) had a significantly greater FTI than non-climbers, a novel finding of this research is that this was only the case when climbers have a best on-sight grade of 25 or greater (Ewbank). MacLeod et al. (2007) suggested that as climbers were more accustomed to producing maximal efforts, they would have exhibited a larger central command-mediated pressor response. However, as this was not shown during the sustained response it seems unlikely to be an effect of just being accustomed to working maximally. Furthermore, Table 8.6 suggests that during the intermittent test, the FTI was greater in all climbing groups compared to non-climbers, suggesting a trainable effect (the FTI explained 26% of the variance between groups). A greater BF and a significantly greater re-oxygenation and HR response during the rest periods (3s) in the intermittent protocol may help to better explain the differences between elite climbers and non-climbers. This seems particularly probable as Philippe et al. (2011) reported that there were significant differences in the FTI between World Cup climbers and non-climbers for both the sustained and intermittent contractions. The authors also reported a significantly greater *absolute* re-oxygenation during the intermittent contraction rest phases. Unfortunately, the authors did not report any data on the de-oxygenation which occurred during the preceding contraction periods.

Data from study two suggests that the intermittent FTI was significantly greater in the elite group compared to all other ability groups. This may be explained by the greater de-oxygenation during the contraction phase, as well as re-oxygenation and increased BF during the rest phases (Table 10.8, Table 10.9 and Table 10.12 ). MacLeod et al. (2007) and Philippe et al. (2011) showed that there was a significantly greater re-oxygenation during the middle and last rest phases in climbers. Rest phase re-oxygenation was defined as the difference between the start of the rest phase and the end of the rest phase. However, this only accounts for the *absolute* change and not one that is *relative* to the amount of de-oxygenation that occurred during the preceding contraction. Study two suggests that the elite group had a significantly greater *absolute* re-oxygenation (Figure 10.1 and Figure 10.2) compared to the control and intermediate groups, however, they also had a greater level of de-oxygenation. Furthermore, when data is presented as *relative* re-oxygenation there were no significant differences



between groups, suggesting that the amount of de-oxygenation may be an important determinant of the significantly greater FTI seen in the elite group.

More specifically, Figure 10.1 and Figure 10.2 show similar significant *absolute* re-oxygenation findings to that of MacLeod et al. (2007) and Philippe et al. (2011) in both the FDP and the FCR. Data from study two suggests that the FDP in the elite group had a significantly greater *absolute* re-oxygenation than all other groups during the first and middle phases, but not the last. In the FCR the elite group had a significantly greater *absolute* re-oxygenation than all groups during the middle phase, and a significantly greater *absolute* re-oxygenation than just the intermediate and control groups during the first and last phases. However, Figure 10.3 and Figure 10.4 suggest that although there were significant differences in *absolute* re-oxygenation during the rest phases, when re-oxygenation was expressed *relative* to the amount of O<sub>2</sub> used within the muscle during the previous contraction, re-oxygenation was not enough to return the O<sub>2</sub>% to the pre-contraction level (0%) until the last contraction phase (and this was only seen in the advanced and elite groups). Furthermore, there were minimal differences in *relative* re-oxygenation between the ability groups in the FDP (Figure 10.3) and the FCR (Figure 10.4). The amount of *relative* de-oxygenation is particularly important and should not be overlooked. This is particularly important as muscle oxidative rate measured using NIRS has been significantly correlated to PCr re-synthesis (measured by 31-magnetic resonance spectroscopy after exercise) (Hamaoka et al., 1996; Sako, Hamaoka, Higuchi, Kurosawa, & Katsumura, 2001). The re-oxygenation in respect to the greater de-oxygenation may provide a better representation of the PCr re-synthesis during the intermittent contractions within the current study, as well as a potential for a denser capillary bed within the muscle.



**Figure 11.2** Example near infrared spectroscopy traces for a control (A), intermediate (B), advanced (C) and elite (D) participant during the baseline, *intermittent* contractions and passive recovery.

Data in study two suggests that the differences in FTI between the groups during the intermittent test may not be due solely to *absolute* tissue re-oxygenation. These differences may be in part due to the larger amount of intramuscular  $O_2$  used during the contraction (10s) phases, and consequently ATP may be produced from different metabolic processes. It is possible that climbers in the current study, who had higher on-sight grade, were able to de-oxygenate the FDP more as they may be able to recruit more muscle fibres, and rely to a greater extent on localised aerobic capacity. Furthermore, the larger amount of  $O_2$  which is paid back during the 3s rest phase may have come from an increased aerobic contribution, as a consequence of the increased trend in  $\Delta$  BF and the significant increase in release HR and  $\Delta$  HR in the elite group upon the release of intermittent contractions (Table 10.12 and Table 10.13), or an increase in the ability of elite climbers to more efficiently off-load  $O_2$  from  $HbO_2$ . Previously, Gaitanos, Williams, Boobis, and Brooks (1993) investigated muscle metabolism during and after intermittent running sprints to failure. The authors reported that during the latter sprints there was a considerable reduction in ATP being generated

through anaerobic processes, and a 10-fold decrease in the rate that glycogen was degraded to BLA. The increase in ATP being generated from aerobic processes was matched by a decrease in muscular power output when attempting to run maximally. It seems possible that elite level climbers in study two had a significantly greater FTI as they may have been more reliant on slow rate glycolysis, whilst non-climbers and lower level climbers may rely more heavily on fast rate.

Despite the significantly greater MVC in study two, a potential increase in type I muscle fibres due to the significantly greater training frequency (Table 9.1) in the elite group could help to explain the greater FTI. An increase in type I fibre has been suggested to allow a muscle to be more active with lower tissue oxygenation levels during contraction (Pereira et al., 2007). Previous studies have shown that lower level rock climbers have higher levels of BLA compared to more advanced climbers, even after pre-practising a route and becoming more accustomed to the moves (Bertuzzi et al., 2007). However, as we did not directly measure the metabolic products within the muscle, or fibre type distribution, this theory is merely speculation. The greater FTI seen in the elite climbers could be due to a number of factors which are associated with trained athletes: a faster metabolic clearance (Jones & Carter, 2000; Tomlin & Wenger, 2001), a greater energy contribution from oxidative-phosphorylation (Holloszy & Coyle, 1984; Jones & Poole, 2005), an increased presence of the metaboreflex (Cornett et al., 2000) or neurological adaptations (España-Romero & Watts, 2012).

The potential for intramuscular adaptation in elite climbers was highlighted by the work of España-Romero and Watts (2012). The authors showed that although climbers had significantly greater finger flexor strength compared to non-climbers, there was no hypertrophy in the forearms. In addition, Ferguson and Brown (1997) suggested that a reduced pressor response seen in trained climbers during intermittent contractions could be brought on by a reduction in metabolic by-products causing less stimulation of chemosensitive afferent nerve endings. It is well known that the peripheral effects of endurance performance on metabolic products has been shown to reduce many metabolites which stimulate chemosensitive nerve endings (Gibala et al., 2006; Holloszy, 1967, 1975; Holloszy & Coyle, 1984). Ferguson and Brown (1997) also suggested that even if metabolic adaptation did not occur then the reduced pressor response could be due to the fact that the afferent nerve endings were desensitised to the build up in metabolites. However, it would seem unlikely that nerve ending

desensitisation was the cause of the greater FTI, as previous research has shown that BLa concentrations were lower in higher level climbers compared to lower level climbers, whilst O<sub>2</sub> consumption was higher (Bertuzzi et al., 2007).

A lower BLa concentration could also be caused by non-active muscles being more efficient at using BLa from the forearms. Blood lactate has previously been shown to be used in non-exercising muscle during exercise (Hermansen & Stensvold, 2008; Jorfeldt, 1970). Furthermore, as the elite and advanced groups trained significantly more, an improved BLa clearance may have occurred. Blood lactate clearance has previously been shown to be enhanced in trained individuals (Donovan & Brooks, 1983; Jones & Carter, 2000; Spengler, Roos, Laube, & Boutellier, 1999; Tomlin & Wenger, 2001). As study two did not measure muscle fibre type distribution or direct muscle metabolism of BLa, these postulations are merely speculative and a further study is required to solidify these theories.

### **11.5 Maximal de-oxygenation**

Data on maximal de-oxygenation presented in Table 10.6 and Table 10.10 contradicts both MacLeod et al. (2007) and Philippe et al. (2011). MacLeod et al. (2007) suggested that non-climbers de-oxygenated the FDS more than the climbers during the sustained test. Philippe et al. (2011) reported no significant differences in de-oxygenation of the FDP between World cup level climbers and non-climbers, as well as no gender differences. Interestingly this study found that this was not the case. Figure 11.1 and Figure 11.2 presents sustained and intermittent contraction examples of de-oxygenation profiles of all ability groups measured within study two. Mean  $\pm$  SD for maximal de-oxygenation in the FDP presented within Table 10.6 and Table 10.10 suggests that the elite group de-oxygenated significantly more compared to all other groups during the sustained and intermittent contractions. In the FCR the elite group de-oxygenated significantly more than the intermediate group during the sustained contraction, but not the intermittent. Furthermore, the current study was the first to report upon the speed of de-oxygenation (Table 10.6) (during the sustained contraction only). In the FDP the elite group de-oxygenated more per second than all other groups. In the FCR the elite groups de-oxygenated significantly more per second than the intermediate group.

Findings of study two suggest that higher ability climbers are able to de-oxygenate the FDP and FCR (more so the FDP) more than lower ability climbers and non-climbers during both sustained and intermittent contractions. The differences between this study and that of MacLeod et al. (2007) may be explained by the difference in forearm flexors used. MacLeod et al. (2007) assessed oxygenation in the FDS, which due to its anatomical location (it lays in the deepest compartment of the forearm) is very difficult to locate, and it is questionable whether NIRS can fully penetrate to such a depth. Conversely the FDP bends fingers two, three four and five is easier to locate on the forearm.

A greater training frequency and duration seen in the elite and advanced climbers may help to explain the maximal de-oxygenation differences. Long term endurance training studies have shown that with an increase in training there are increases in type I fibre (Russell et al., 2003). Training for rock climbing consists of intense maximal efforts for climbs between two and four minutes in duration, followed by rest periods before the next route/ascent. This style of exercise training is similar to interval training. Muscle biopsy has shown that interval training increases oxidative capacity and type I muscle fibre contribution (Henriksson & Reitman, 1976; Simoneau et al., 1985), and anecdotally interval training in rock climbing has been suggested to increase performance (Horst, 2008). Therefore, an increase in type I muscle fibre composition may help to explain the greater de-oxygenation seen within the elite group during the current study. Further investigations which directly assess muscle fibre type would clearly help to clarify these potential differences and adaptations within the musculature.

Data in study two suggests that elite rock climbers are able to significantly de-oxygenate the FDP and the FCR more than lower grade climbers during sustained and intermittent contractions (particularly the FDP). It is possible the degree of de-oxygenation for elite climbers within the current study was related to the significantly greater amount of training undertaken (Table 9.1). Exercise training has been shown to increase both skeletal muscle mitochondrion content and oxidative enzyme activity (Burelle & Hochachka, 2002; Uchiyama, Miaki, Terada, & Hoso, 2011). Although muscle mitochondrial capacity was not measured within this study, it is possible that the significantly greater amount of training seen in the elite and advanced rock climbers may have induced muscular adaptations. Furthermore, España-Romero and Watts

(2012) suggested that the differences in forearm strength between elite and non-climbers were either due to neurological adaptation, activation of more muscle fibres or a greater capillary density. It has also been previously shown that endurance training, even over a short period of time can increase muscle capillary density to over 31% (Costes et al., 2001). Although study two did not measure forearm volume or mitochondrion density, the current findings build upon evidence which suggests that elite rock climbers may potentially be able to recruit more muscle fibres and have an improved oxidative capacity within the FDP and FCR. Further investigation into mitochondria content and oxidative enzyme activity with the flexors of a range of different ability rock climbers would aid in confirming this theory.

### **11.6 Time to half recovery**

To my knowledge study two is the first to assess tissue re-oxygenation time to half recovery in the forearm flexors of rock climbers. As previously mentioned, re-oxygenation is particularly important to climbers as muscle oxidative rate measured using NIRS has been significantly correlated to PCr re-synthesis (Hamaoka et al., 1996; Sako et al., 2001). However, the lack of research in rock climbing is not unsurprising as even within mainstream sports there is limited evidence for the effects of exercise training on muscle oxygenation kinetics during and after exercise (Uchiyama et al., 2011). Findings from study two not only show that maximal de-oxygenation was significantly greater in elite rock climbers (Table 10.6 and Table 10.10), but the time to half recovery was also significantly faster in the elite compared to all other climbers. More specifically, within the FDP the elite group had a significantly faster time to half recovery than all other groups, and the advanced group was significantly faster than the control and intermediate groups. Furthermore, the O<sub>2</sub>% rise per s followed the same pattern. The small SD seen in the elite and advanced groups (Table 10.6 and Table 10.10) for maximal de-oxygenation and time to half recovery suggest that the climbers may have been close to the physiological limit of being able to use O<sub>2</sub> within the muscle. Furthermore, the data may suggest that post-contraction to failure, BF may not play such an important role, and what may be more important is what happens to the blood once it reaches the muscle; for example the ability for HbO<sub>2</sub> to off-load O<sub>2</sub> within the muscle.

A further interesting finding of the study was that the significant differences in half time to recovery were seen after both sustained and intermittent contractions-to-failure within the FDP. Although the responses for the FCR post-sustained and intermittent contractions were similar to each other, they were not identical and recovery was not as quick as seen within the FDP. In the FCR post-sustained contraction the elite and advanced groups had a significantly faster half time to recovery compared to the intermediate group only. After the intermittent contractions the elite and advanced groups had a significantly faster time to half recovery than the control group only. The differences between the FDP and the FCR suggest that the adaptations may be localised and occur at the muscular level. Further investigation into a variety of forearm flexors may help to reveal which are the most specific to the sport of rock climbing.

Whilst the significant difference may have been due to genetic inheritance, it can be speculated that as the elite and advanced climbers recovered significantly faster than both intermediate and control groups, the underlying adaptations for this quicker recovery are likely to be associated with climbing specific training. Table 9.1 suggests that climbing experience (years), climbing sessions per week and hours climbing per week were all significantly higher in the elite compared to the advanced and intermediate groups, and the advanced were significantly greater than the intermediate group. Rock climbing is a mixture of dynamic and static muscle contraction, of which both involve a notable amount of resistance exercise in the form of the arms. Specifically, the FDP and FCR contract in conjunction with the legs pushing the body up vertical and over-hung sections of wall. Muscular adaptations due to the nature of the training and activity have been well documented in rock climbing studies (López-Rivera & González-Badillo, 2012; Phillips et al., 2012; Schweizer et al., 2007) but no known study has directly measured oxidative and non-oxidative capacity or enzymatic concentrations within the skeletal muscle. Therefore, it is difficult to ascertain definitive conclusions regarding the amount of aerobic/anaerobic contribution in the forearm flexors of rock climbers. However, NIRS offers an excellent non-invasive measure of tissue re-oxygenation and de-oxygenation, as well as an indicator of PCr re-synthesis. The significant differences in time to half recovery seen within Table 10.6 and Table 10.10 may be due to the elite and advanced rock climbers being able to re-synthesis PCr faster than non-climbers. Furthermore, previous studies have suggested that a delay in the re-oxygenation of non-trained individuals (compared to elite rowers) may be due to

an increased time in which the re-synthesis of PCr to phosphate occurs (Chance et al., 1992).

There are numerous factors which may contribute to the slow increase in re-oxygenation seen within the intermediate and control groups. Ogata et al. (2008) assessed skeletal muscle re-oxygenation post-HGD exercise and reported slow rates of recovery in non-forearm trained individuals, similar to those seen in the intermediate and control groups in study two. The authors suggested that slow re-oxygenation may have been due to an almost immediate withdrawal of the central command post-exercise, as HR had returned to baseline values within 30s of exercise cessation. However, this may not be the case for the elite and advanced climbers within my study. Table 10.5 suggests that the mean change in HR during the sustained contraction had an increasing trend with increased ability group; and during the intermittent contractions the release HR and the  $\Delta$  HR (difference between contraction and release) were significantly higher in the elite and advanced compared to the control and intermediate groups. Although post-exercise HR was not measured in my study, findings suggest a quick withdrawal of the central command may only be relevant to non-trained individuals, and not in trained rock climbers who may have altered responses occurring during the contraction as well as post-contraction.

## **11.7 Conclusion**

When sport specific grip strength, and strength-to-weight ratio are assessed in a range of different ability rock climbers, they appear to be accurate measures of rock climbing performance, accounting for 36 and 49% of the variance between groups, respectively. It would appear that an increased MVC may not be associated with greater BF occlusion in elite level climbers as previous research suggested. It is possible that these increasing trends in BF during a sustained contraction seen in the current study could be further elevated in World Cup level climbers which may in part explain the greater FTI reported by Philippe et al. (2011). The significantly greater FTI seen during the intermittent contractions to failure in study two may be related not only to the significantly greater *absolute* re-oxygenation, but also the extent of de-oxygenation during the preceding contraction. Therefore, future studies should report re-oxygenation as a *relative* value as well as *absolute*. This greater de-oxygenation and significantly



greater re-oxygenation seen in the elite group during the intermittent contractions may occur due to an increase in  $\Delta$  BF as well as a significant increase in release HR and  $\Delta$  HR during the intermittent rest phases.

Study two suggests that as ability level increases climbers are able to maximally de-oxygenate both the FDP and the FCR more. Even when this greater maximal de-oxygenation is taken into consideration, the time to half recovery in both the FDP and the FCR after both sustained and intermittent contractions were significantly faster in elite and advanced rock climbers. This greater de-oxygenation and increased speed of recovery may be due to higher level rock climbers having a greater oxidative capacity, an increased capillary density, and/or a greater influence of the metaboreflex. Further research investigating definitive existence and trainability of these variables is warranted.

The following chapter 'General Conclusion' aims to draw together the findings from both study one and study two. The chapter aims to highlight the psychological and physiological contributions during on-sight rock climbing, as well as the potential differences in the haemodynamic response to maximal contractions in elite, advanced and intermediate rock climbers.

## General Conclusions

Previous rock climbing research attempted to determine the physiological responses underpinning different ability groups ascending under numerous conditions, mainly top rope and lead. However, due to the lack of psychophysiological studies there are currently limitations for the interpretation of physiological data. Gaining an understanding of the potential nervous response, and how it may affect physiological function has only been studied in intermediate level climbers and speculated upon in other ability groups. These limited previous studies suggested that in intermediate climbers, elevated levels of pre-climb anxieties were higher during on-sight lead ascents compared to top roped climbs, and that the degree of anxiety was significantly correlated to the cortisol response. This elevation in psychological stress during on-sight climbing was suggested to have caused significantly higher HR responses, and BLa concentrations. However, there has been no known research which has investigated the potential differences in the nervous response in multiple ability groups or ascent styles.

The purpose of study one was twofold, 1) to examine the psychological and physiological responses to difficult on-sight climbing with respect to ability level, and 2) examine the effects of ascent style (lead vs top rope) on the above responses. Results from study one suggested that there were no significant differences or notable trends between ability groups or ascents styles in any pre-climb anxieties, pre-climb HR,  $\dot{V}O_2$  or cortisol (psychological component) responses. However, the elite climbers had significantly higher cortisol response (performance component) response and average  $\dot{V}O_2$  compared to the intermediate and advanced groups. Furthermore, the elite group had a significantly higher average HR response compared to the intermediate group. This was matched with significantly higher post-10 minute BLa concentrations within the intermediate group. The intermediate group also took significantly longer to ascend on lead compared to top rope.

The intermediate and advanced groups spent significantly longer in a static position compared to the elite group. However, more importantly the *percentage of static time which was spent resting* whilst climbing was significantly higher in the elite climbers compared to all other groups. Findings from study one suggest that when on-sight rock

climbing there are no differences in the nervous response either between ability groups or between ascent styles. The heightened climb average  $\dot{V}O_2$ , HR and cortisol responses may be caused by the physical increase in route difficulty. Furthermore, whilst ascending a route it would appear that elite climbers use the rest periods to shake out the hands and forearm flexors, something not seen in the intermediate group. It is possible that these rest periods may affect muscular efficiency and therefore the aerobic/anaerobic contributions within the forearm flexors. However, the effects on the haemodynamic responses and the extent of these effects are not known and have not been studied in multiple ability groups of rock climbers.

The purpose of study two was to determine whether there were ability group differences in the haemodynamic responses within the FDP and FCR during sustained and intermittent contractions-to-failure at 40% of MVC. Results from study two suggested that with increased climbing ability there is a concurrent increase in the FTI during the intermittent test only. As *relative* re-oxygenation was not different between ability groups in either the FDP or FCR, the increased FTI may be a cause of both the significantly greater amount of de-oxygenation as well as the *absolute* re-oxygenation which occurred in both the FDP and FCR during the rest periods, or the significantly higher release HR and  $\Delta$  HR that occurred during this time.

During the post-exercise recovery period, the majority of the intermediate and control participants did not fully re-oxygenate back to baseline values within the five minute period. The time to half recovery within the FDP was significantly faster in the elite and advanced groups compared to both the intermediate and the control groups; in the FCR this was significantly faster in the elite compared to the intermediate group, after both sustained and intermittent contractions. Findings from study two suggest that the significantly greater maximal de-oxygenation and increased speed of recovery may be due to higher level rock climbers having a greater forearm oxidative capacity, increased ability to re-synthesis PCr, an increased capillary density or a greater presence of the metaboreflex. Further research is required to determine the definitive causes, and why these differences occurred, and if they are trainable.

### **12.1 Key findings**

1. There appears to be no differences in pre-climb anxieties either between ability groups or ascent styles.
2. The higher performance-cortisol,  $\dot{V}O_2$  and HR responses in the elite group measured during, as well as post-climb, are likely a cause of the increased physical difficulty of a route.
3. There appears to be an increased reliance on the aerobic metabolism with the increase in ability level.
4. The elite group had a significantly greater re-oxygenation during the rest periods seen in the intermittent test, and therefore the climbers may gain greater benefits from more frequent rest periods during their ascents.
5. The greater re-oxygenation and higher HR responses during the rest periods of the intermittent test may have caused the increased FTI.
6. Training both the FDP and the FCR using sport specific grip techniques is likely to contribute to an increase in climbing performance.













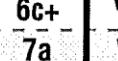










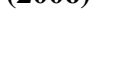





### **12.2 Future directions**

1. Are there ability group or ascent style differences in pre-climb anxieties for those climbers who have a best on-sight grade of < 17 (Ewbank)?
2. Do climbers who have a best on-sight grade of > 29 (Ewbank) use a greater contribution of their aerobic capacity when ascending at the top of their ability compared to lesser ability climbers?
3. Are there ability group differences in personality traits?
4. Are there ability group differences in appraisal or toughness theories?
5. Are there differences in *absolute* and *relative* re-oxygenation, BF, HR and FTI during sustained contractions to failure in climbers with a best on-sight grade of > 29 (Ewbank)?
6. Are there ability group differences in the capillary density of the FDP and FCR?
7. Is there a greater presence of enzymes associated with the aerobic metabolism in the FDP and FCR of elite rock climbers during fatiguing contractions?
8. What is the optimal training method for increasing the de-oxygenation, and subsequent re-oxygenation of the FDP and the FCR in rock climbers?

9. Are there ability group differences in the pressor response both during and after sustained and intermittent contractions?
10. Do higher level rock climbers have an increased metaboreflex?

## Appendix A

### Route Grades Conversion Table (Giles et al., 2006)

<b>R O U T E   G R A D E S</b>				
<b>BRITISH TRAD GRADE</b> (For well-protected routes)	<b>Sport Grade</b>	<b>UIAA</b>	<b>USA</b>	<b>Australian</b>
	1	I	5.1	4
	2	II	5.2	6
	2+	III	5.3	8
	3-	III+	5.4	10
	3	IV	5.5	12
	3+	IV+	5.6	14
	4	V	5.7	16
	4+	V+	5.8	18
	5	VI-	5.9	20
	5+	VI	5.10a	22
	6a	VI+	5.10b	24
	6a+	VII-	5.10c	26
	6b	VII	5.10d	28
	6b+	VII+	5.11a	30
	6c	VIII-	5.11b	32
	6c+	VIII	5.11c	34
	7a	VIII+	5.11d	36
	7a+	IX-	5.12a	38
	7b	IX	5.12b	40
	7b+	IX+	5.12c	42
	7c	X-	5.12d	44
	7c+	X	5.13a	46
	8a	X+	5.13b	48
	8a+	X-	5.13c	50
	8b	X	5.13d	52
	8b+	X+	5.14a	54
	8c	XI-	5.14b	56
	8c+	XI	5.14c	58
	9a	XI+	5.14d	60
	9a+		5.15a	62

Appendix A 12-1 Grade conversion table reproduced from Rockfax (2002). Giles et al., (2006)

## Appendix B

### Bouldering Grades Conversion Table

V Scale	Fontainebleau Scale	British Technical	
VB			> 5a
V0-	4	5a	
V0	4+		5b
V0+	5		
V1	5+	5c	
V2	6a		
	6a+		6a
V3	6b		
V4	6b+	6b	
	6c		
V5	6c+		
V6	7a		
V7	7a+		6c
	7b		
V8	7b+		
V9	7c	7a	
V10	7c+		
V11	8a		
V12	8a+		7b
	8b		
V13	8b+		
V14	8c		
V15	8c+		

**Appendix B 1 A comparative table of the major grading systems in bouldering**

## Appendix C

### Full Recovery Data (NIRS re-oxygenation)

**Table I Shows mean  $\pm$  SD full recovery characteristics for the sustained and intermittent contractions**

		Sustained contraction		Intermittent contraction	
		Time to full recovery s (mean $\pm$ SD)	Full recovery O <sub>2</sub> rise $\cdot$ s (mean $\pm$ SD)	Time to full recovery s (mean $\pm$ SD)	Full recovery O <sub>2</sub> rise $\cdot$ s (mean $\pm$ SD)
<b>FDP</b>					
	Control	195.93 $\pm$ 24.56	0.16 $\pm$ 0.04	179.2 $\pm$ 63.84	0.12 $\pm$ 0.06
	Intermediate	146.49 $\pm$ 81.9	0.37 $\pm$ 0.3	169.33 $\pm$ 68.24	0.2 $\pm$ 0.13
	Advanced	80.59 $\pm$ 82.99	1.59 $\pm$ 1.5	59.43 $\pm$ 85.62	2.25 $\pm$ 1.88
	Elite	60.83 $\pm$ 91.85	2.92 $\pm$ 1.89	20 $\pm$ 17.1	2.85 $\pm$ 1.65
<b>FCR</b>					
	Control	96.22 $\pm$ 66.65	0.24 $\pm$ 0.18	182.67 $\pm$ 58	0.11 $\pm$ 0.05
	Intermediate	110.4 $\pm$ 69.75	0.12 $\pm$ 0.08	167.2 $\pm$ 78.91	0.08 $\pm$ 0.06
	Advanced	68.92 $\pm$ 72.85	1.31 $\pm$ 1.05	100.5 $\pm$ 111.7	0.71 $\pm$ 1.13
	Elite	98.98 $\pm$ 98	1.1 $\pm$ 1.13	41 $\pm$ 39.24	1.02 $\pm$ 0.75

#### Sustained full recovery characteristics

##### Time to recovery

As can be seen in Table I the time taken for the FDP to fully recover post sustained contraction appears to of decreased as the climbing ability increased. Mean  $\pm$  SD were large across all rock climbing ability groups, but not in the control group where in relation to the long recovery time, SDs were relatively small. The time taken for the FCR to fully recover does not follow the same trend as the FDP. All recovery times were faster in the FCR than the FDP with the exception of the elite group. Furthermore, within the FCR muscle there were minimal differences between the control, intermediate and elite recovery times.



### ***Oxygen Saturation rise per second***

Table I suggests that oxygenation rise ·s in the FDP increases from control through to elite climbers. Mean  $\pm$  SD show that both the advanced and elite groups had a notably larger O<sub>2</sub> % rise ·s than the control and intermediate groups. Furthermore, Table I shows that the oxygenation rise ·s within the FCR is small for both the control and intermediate groups, whereas comparatively the advanced and elite climbers appear to have a similarly greater O<sub>2</sub> % rise ·s. Due to the incomplete data set described in section Appendix C, no statistical analysis was performed on this data.

### **Intermittent full recovery characteristics**

As seen with the sustained contraction not all participants managed to fully recover within the five minute recovery period. For the FDP only 5, 6, 7 and 8 participants fully recovered in the control, intermediate, advanced and elite groups respectively. For the FCR only 6, 5, 8 and 8 participants fully recovered respectively. As the data set is incomplete statistical analysis was not performed on this data set. However mean  $\pm$  SD are presented in Table I.

### ***Time to recovery***

Mean  $\pm$  SD presented in Table I suggest that it took both the control and intermediate groups notably longer than the advance and elite groups to recover. The mean recovery times for the FDP and the FCR are very similar for all ability groups.

### ***Oxygen Saturation rise per second***

Mean  $\pm$  SD presented in Table I suggest the control and intermediate groups had a very small ·s recovery rate of O<sub>2</sub>%. This response was the same for both the FDP and the FCR. Although the advanced groups had a slightly smaller ·s recovery rate compared to the elite group, they both were notably greater than the control and intermediate groups. However, the size of the ·s recovery was smaller in the FCR compared to the FDP for both the advanced and elite groups.

## Appendix D Coefficient of Variation for the Fingerboard Apparatus

To determine the coefficient of variation for the climbing ergometer, fifteen male participants were asked to attend two sessions separated by 24 hours. During each session the participants performed the same warm up as described in section 9.2.1. This was followed by three MVC trials each separated by 60s. If the participant scored the highest MVC during the third trial then a fourth was conducted. The mean averages of the MVC attempts during session one and session two are presented below in Table D1.

**Table D1** mean averages for the MVC trials during sessions one and two

Participant number	Session one	Session two
1	17.34	18.95
2	32.64	31.89
3	27.32	31.89
4	17.95	18.64
5	22.12	22.45
6	24.79	24.29
7	21.43	21.69
8	25.84	25.3
9	24.45	24.97
10	21.09	20.87
11	18.49	18.98
12	24.65	25.04
13	27.02	26.67
14	18.98	19.23
15	17.69	18.01
	Mean = 4.4	Mean = 4.18

CV for duplicates =  $(CV = (SD \text{ of difference between duplicate samples} / \text{mean of all samples}) \times 100)$

Combined mean = 23.02233

SD of difference = 4.4 – 4.18

SD of difference = 0.107286

$CV = 0.107286 / 23.02233 \times 100$

**CV = 0.46%**

**Appendix E** Pilot Study: One Fryer, S., Draper, N., Dickson, T., Blackwell, G., Winter, D., & Ellis, G. (2011). Comparison of Lactate Sampling Sites for Rock Climbing. *International journal of sports medicine*. 32: 428 – 432

<http://dx.doi.org/10.1055/s-002-22055>

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**Appendix F** Pilot Study Two: Fryer, S., Hillier, S., Dickson, T., Draper, N., Stoner, L., Winter, D., Young, J., Cohen, L. (2012). Capillary cortisol sampling during high-intensity exercise. *International journal of sports medicine*. 33: 842-845

<http://dx.doi.org/10.1055/s-002-23768>

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**Appendix G** Pilot Study Three: Draper, N., Couceiro, J., Fryer, S., Dickson, T., Winter, D., Ellis, G., et al. (2011). Reporting climbing grades and grouping categories for rock climbing.  
*Isokinetics and exercise science 19 (4)*, 1-8

# Reporting climbing grades and grouping categories for rock climbing

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**Abstract.** Rock climbing is an increasingly popular adventure sport with a growing research base. To date the growth of research and reporting styles has been somewhat haphazard and as a consequence comparison between studies can be problematic. The aim of this paper was to make suggestions about a number of changes that could be made to improve the consistency in reporting between studies. Included with this paper are two new tables, one each for male and female climbers. These provide comparative grading scales for use in reporting for future studies. These tables also provide a suggested framework for grouping climbers according to their ability. Using the tables researchers could group the climbers in their study by a category name (lower grade, intermediate, advanced, elite or higher elite climber) or by a number (level 1–5). In addition, the authors make recommendations about climber characteristics that could usefully be reported in future to assist comparison between studies. It would be helpful to readers if the self-reported, highest lead climbs (on-sight and redpoint) could be reported for a climbing group, along with the types of climbing regularly undertaken.

**Keywords:** Rock climbing, grade tables, climbing grades, Ewbank scale, Yosemite decimal scale, sport climbing

## 1. Introduction

Commonly known as rock climbing, the sport actually comprises a number of different disciplines that require individual research attention to develop a more complete understanding of the performance dynamics for each strand. Perhaps the oldest discipline, which grew from mountaineering, is that of traditional or “trad” climbing. Trad climbers ascend routes using a rope and carry all protection with them as they ascend the route [1]. At various points on the route a climber will stop to place anchors (wires, camming devices and slings) into/around appropriate points on the rockface and clip these to the rope to protect against a possi-

bly fatal ground fall. One of the most commonly pursued disciplines is that of sport rock climbing which is also one of the safest forms of the sport. As such it has become one of the main disciplines researchers have concentrated upon when investigating the physiological, psychological and technical aspects of the sport. Climbers ascend routes, again protected against a ground fall by a rope, but instead of placing their own protection anchors the climbers clip the rope to anchors that have been pre-drilled and set into the rock [2]. Virtually all indoor climbing with ropes uses this method and it forms the predominant version of the sport for outdoor climbing in Europe. Indeed most competition climbing takes place using this modality. These descriptions of trad and sport climbing are known as lead climbing ascents. Lead climbing involves the climber wearing a harness to which a rope is attached. As the climber ascends the route they clip it to the anchors while being belayed from the ground [3,4].

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Another popular climbing discipline is bouldering which usually takes place on shorter (less height gain) routes without the use of rope, but with a mattress (bouldering mat) placed beneath the climber to protect against injury in the event of a ground fall [5]. Bouldering is increasing in popularity, perhaps due to the purity (the climber ascends the route without having to stop to place gear or wearing harness/trailing a rope) and speed at which you can move between routes. There are an increasing number of research papers that focus on this discipline within the sport [6,7].

As well as the different disciplines within rock climbing, the style of lead climb ascent of a specific route can also be described differentially to clarify the way in which it was made. To claim completion of a climbing route an ascent would have to be as a lead climb without weighting the rope (resting hanging on the rope) during the climb. An on-sight ascent would be a climb completed without the climber having any information about how to complete the route [8–11]. This style is widely used in competition climbing. If on the other hand, a climb was made first time, but having watched a previous climber ascend the route or having gained information about the route prior to ascent the term “flash” is commonly used to describe the ascent. Finally if a route is completed after practicing the route before a clean ascent the term “redpoint” is used to describe the achievement. To practice a route a climber may either lead climb or top-rope the route. Top-roping is where the climber is belayed by a rope anchored from the top of the route and so they do not have to place protection as they make the ascent [3,4,9].

The increasing popularity of the sport and the development of competition formats have perhaps been the major stimuli for the rapid increase in rock climbing research in recent years [12,13]. There have now been over 250 original research papers published in the field and the past decade has seen a rapid increase in research interest worldwide [14]. Early studies in the field of rock climbing tended to focus on the anthropometry of climbers, the incidence and types of injuries associated with the sport and the underlying physiological components of climbing [15–28]. More recently researchers have begun to examine factors that affect performance and to identify climbing specific training methods [2, 29]. Associated with this work has been a move to investigate the interaction of the key performance variables and the development of sport specific assessment tools for climbing [1,12,13,30].

Researchers in the field have tended to concentrate upon their specific research interests and as such the

development of knowledge in the field has been somewhat haphazard. In addition, the fragmented nature of the sport's research development has meant that the reporting methods have differed between studies which has made comparison between studies more problematic. As a consequence, the aims of this paper are to; (a) recommend a standardised method for reporting the characteristics of participants in future climbing studies, (b) to propose two ability classification tables for males and females which could be used in future studies to report on participant climbing ability levels and (c) to suggest the use of a comparison grading scale (that could be used in addition to the country/region scale where the data were collected) that would be helpful for statistical analysis.

## 2. Reporting climber characteristics

In the participants or subjects section of the method researchers to date have used a variety of measures for reporting the characteristics of their climbers. This variation and often lack of information, particularly in papers published before 2000, means the reader is often left with further questions about the participant group. This inconsistency also adds to the difficulties of making comparisons between studies. The situation is changing and a number of recently published papers have added points that could be adopted for all studies. Clearly studies should present basic biographical data such as age, height, mass, body fat percentage and aerobic capacity. In addition key climbing specific factors include the climbing ability of the group, years of experience in climbing, days of training and hours of training per week and the main types or disciplines followed. Recent papers by MacLeod et al. [31], Schöffl et al. [32], España Romero et al. [33] and Sherk et al. [34] have provided more informed details about the climbing ability of their participants, including their self-reported highest current on-sight and redpoint lead climbs. This type of information is very helpful to the reader and given the findings of Draper et al. [35] self report climbing grades appear to be a valid and reliable indicator of climbing ability. The main disciplines or types of climbing undertaken by climbers also merit reporting in the participants section as this provides additional information about the training status of the recruited climbers. For instance Schuster et al. [36] provided an excellent breakdown of the main types of climbing undertaken by their participants (tradition climbing, sport, mostly sport some traditional,

gym climber etc.) and this system might usefully be adopted for reporting participant characteristics in future climbing studies.

There is additional information that could also be added to the procedures section for comparative purposes. It would be very useful to the reader if researchers made clear the venue where the climbing took place, the nature of the protection available, the safety rope protocol (lead or top-rope) and amount of practice on and/or knowledge of the route climbers had prior to completion of the data collection.

### 3. Ability classification tables for male and female climbers

There are times in rock climbing research when it is helpful to describe the ability of the study group or groups within a study. The nomenclature used by researchers to describe individual climber and group abilities has varied widely between studies. Common examples include the use of the term "recreational" climber or group which has been used across studies to describe a wide variety of climber ability groups from beginner to elite level climbers. In the context of climbing this term is perhaps particularly unhelpful as anyone who is not a full-time professional climber is by definition recreational [37,38]. As a consequence, this group could include climbers just starting out in the sport or those who have been climbing for many years at 8a (sport) and above ability levels. As such this term might not be particularly useful for future studies and we would advocate the non-continuation of the use of this term to describe climber groups in future studies. Another example of confusion that can be created through a lack of agreement in the meaning of terminology is the use of terms "elite" or "expert" to describe an ability group. For this example the ability of the climber necessary to be classified as elite or expert has varied greatly between studies [37–41]. Common agreement between researchers as to what constitutes and elite or expert level climber would be very helpful for comparative purposes.

In 2009 Draper et al. [42] published a table that had been developed for a study regarding the assessment of the validity and reliability of a series of novel, sport specific measures of flexibility for rock climbing. This table consisted of a number of grading scales (Sport grade, British technical grade and Fontainebleau bouldering grade) that had been tabulated in order to make comparison between scales. Divisions were created in

the tables in order to classify the climbers in the study into one of four groups (novice, intermediate, advanced or elite climber). This type of table could be very useful for climbing research, however, there were a number of problems with this iteration that could be improved upon.

Firstly the use of the term "novice" is fraught with the same problems associated with term "recreational". In this context the term could apply to someone just starting out in the sport, but could equally refer to a recreational climber who is unconcerned with climbing high grades routes, but wishes merely to be out climbing. As such this latter type of climber might have many years of experience, have a past on-sight or redpoint grade that was much higher but would be termed incorrectly as a novice climber. Secondly the divisions for each ability grouping were agreed by a small group of expert climbers ( $n = 3$ ). A wider consultation process would perhaps have led to the development of different division points for the classification of each ability group. Thirdly, the table was designed as appropriate for classifying male and female climbers, rather than separate tables being created for each gender. Fourthly, the climbers did not state, especially in the case of sport climbing, whether the highest recorded route was for an indoor (artificial climbing wall) or outdoor natural rock climb. Finally, the authors neglected to state that the highest climb that was recorded for each climber was their redpoint ability rather than on-sight.

Our paper presents two adapted versions of the table presented by Draper et al. [42]. These were developed using the Delphi technique in consultation with over 40 expert climbers and researchers worldwide [43,44]. The classifications are presented separately for females (Table 1) and males (Table 2) as the overwhelming feeling amongst respondents was that such a classification system should be developed as two separate tables. As can be seen from the tables, for lower grade climbers the bounds for the division are the same for males and females, however, for all other categories the suggested boundary grades differ by gender. These divisions were agreed upon through consultation with the expert climbers and researchers involved in the development of the tables. The divisions are intended to reflect, as well as possible, natural breaks climber ability levels. The expert respondents believed there were differences in the climbing abilities for each of these groupings. We recognise that, as with the grading of climbs themselves, there is a relative degree of subjectivity in making these ability grouping distinctions, but we have tried to remain as object as possible in this process by



Table 1  
Climbing grade and climbing group divisions comparison table for female climbers

Ability group	USA	French/sport	British Trad Adj	British Trad Tech	BRZ	Aus/NZ	UIAA	UIAA metric	Watts
Lower Grade (Level 1)	5.1	I	D	I	I sup	9	I		
	5.2	2	VD	2	II	10	II		
	5.3	2+	HVD	3a	II sup	11	III		
	5.4	3-	S	3b	III	12	IV		
	5.5	3	HS	4a	4	13	IV+		
	5.6	3+	VS	4b	5	14	V		0.00
	5.7	4	VS	4c	5	15	V+		0.25
	5.8	4+	HVS	5a	5sup	16	VI-	5.66	0.50
	5.9	5	E1	5b	6	17	VI	6	0.75
Intermediate (Level 2)	5.10a	5+	E1	5b	6sup	18	VI+	6.33	1.00
	5.10b	6a	E2	5c	6sup	19	VII-	6.66	1.25
	5.10c	6a+	E2	5c	6sup	20	VII	7	1.50
	5.10d	6b	E3	6a	6sup	21	VII	7	1.75
	5.11a	6b+	E3	6a	7a	22	VII+	7.33	2.00
Advanced (Level 3)	5.11b	6c	E4	6b	7b	22	VIII-	7.66	2.25
	5.11c	6c+	E4	6b	7b	23	VIII-	7.66	2.25
	5.11d	7a	E4	6b	7c	23	VIII	8	2.50
	5.12a	7a+	E5	6b	8a	24	VIII+	8.33	2.75
	5.12b	7b	E5	6c	8b	25	IX-	8.66	3.00
	5.12c	7b+	E6	6c	8c	26	IX-	8.66	3.25
	5.12d	7c	E6	6c	9a	27	IX	9	3.50
	5.13a	7c+	E7	7a	9b	28	IX+	9.33	3.75
Elite (Level 4)	5.13b	8a	E7	7a	9c	29	X-	9.66	4.00
	5.13c	8a+	E7	7a	10a	30	X-	9.66	4.25
	5.13d	8b	E8	7a	10b	31	X	10	4.50
	5.14a	8b+	E8	7a	10c	32	X+	10.33	4.75
Higher Elite (Level 5)	5.14b	8c	E9	7a	11a	33	XI-	10.66	5.00
	5.14c	8c+	E9	7b	11b	34	XI	11	5.25
	5.14d	9a	E10	7b	11c	35	XI+	11.33	5.50
	5.15a	9a+	E10	7b	12a	36	XI+	11.33	5.75
	5.15b	9b	E11	7b	12b	37	XII-	11.66	6.00
	5.15c	9b+	E11	7b	12c	38	XII	12	6.25

N.B. USA system is the Yosemite Decimal System (YDS). The French/European system is also known as the "Sport Grade System". The Ewbank System is generally common to Australia, New Zealand and South Africa (with some minor differences).

consulting a wide number of expert respondents before finalising each boundary. There will obviously be some overlap in abilities between those very close to a climbing ability boundary, the respondents however, indicated that in their opinion there were different ability groupings across the climber ability continuum. These tables are an attempt to establish such groups to assist with future research.

The number of grading systems has been increased from the table created by Draper et al. [42] to provide a wider range for comparative purposes. The Fontainebleau bouldering grading system was removed, however, as respondent feedback suggested that separate bouldering specific tables would be more appropriate. Given the increasing popularity of bouldering, the number of bouldering specialists the sport now has and the number of grading systems for bouldering it would perhaps be beneficial for similar tables (male

and female) across grading scales to be developed for this discipline of climbing.

The descriptors for the ability grouping have also been modified from Draper et al. [42] in light of consultation feedback. As described above respondents indicated that the term novice be replaced due to its lack of accuracy. The classifier "lower grade" climber has been created as this can encompass both climbers who are new to the sport and those more experienced climbers who climb by choice or ability level at lower grade. The elite climber group, again after feedback from respondents, was sub-divided into two levels as the climbers consulted believe there are two clear sub-group that exists even at the elite level with regard to the ability of higher elite climbers in comparison to elite climbers. Several respondents also suggested that a number system might be added rather than named categories and so we have added this as an alternative for reporting purposes in future studies. As can be seen

Table 2  
Climbing grade and climbing group divisions comparison table for male climbers

Climbing group	USA	French/sport	British Trad Adj	British Trad Tech	BRZ	Ewbank	UIAA	UIAA metric	Watts
Lower Grade (Level 1)	5.1	1	D	1	I sup	9	I		
	5.2	2	VD	2	II	10	II		
	5.3	2+	HVD	3a	II sup	11	III		
	5.4	3-	S	3b	III	12	IV		
	5.5	3	HS	4a	4	13	IV+		0.00
	5.6	3+	VS	4b	5	14	V		0.25
	5.7	4	VS	4c	5	15	V+		0.50
	5.8	4+	HVS	5a	5 sup	16	VI-	5.66	0.75
	5.9	5	E1	5b	6	17	VI	6	1.00
Intermediate (Level 2)	5.10a	5+	E1	5b	6 sup	18	VI+	6.33	1.25
	5.10b	6a	E2	5c	6 sup	19	VII-	6.66	1.50
	5.10c	6a+	E2	5c	6 sup	20	VII	7	1.75
	5.10d	6b	E3	6a	6 sup	21	VII	7	2.00
	5.11a	6b+	E3	6a	7a	22	VII+	7.33	2.25
	5.11b	6c	E4	6b	7b	23	VIII-	7.66	2.25
	5.11c	6c+	E4	6b	7b	23	VIII-	7.66	2.25
	5.11d	7a	E4	6b	7c	23	VIII	8	2.50
	5.12a	7a+	E5	6b	8a	24	VIII+	8.33	2.75
Advanced (Level 3)	5.12b	7b	E5	6c	8b	25	IX-	8.66	3.00
	5.12c	7b+	E6	6c	8c	26	IX-	8.66	3.25
	5.12d	7c	E6	6c	9a	27	IX	9	3.50
	5.13a	7c+	E7	7a	9b	28	IX+	9.33	3.75
	5.13b	8a	E7	7a	9c	29	X-	9.66	4.00
	5.13c	8a+	E7	7a	10a	30	X-	9.66	4.25
Elite (Level 4)	5.13d	8b	E8	7a	10b	31	X	10	4.50
	5.14a	8b+	E8	7a	10c	32	X+	10.33	4.75
	5.14b	8c	E9	7a	11a	33	XI-	10.66	5.00
	5.14c	8c+	E9	7b	11b	34	XI	11	5.25
	5.14d	9a	E10	7b	11c	35	XI+	11.33	5.50
Higher Elite (Level 5)	5.15a	9a+	E10	7b	12a	36	XI+	11.33	5.75
	5.15b	9b	E11	7b	12b	37	XII-	11.66	6.00
	5.15c	9b+	E11	7b	12c	38	XII	12	6.25

N.B. USA system is the Yosemite Decimal System (YDS). The French/European system is also known as the "Sport Grade System". The Ewbank System is generally common to Australia, New Zealand and South Africa (with some minor differences).

in the tables the scale ranges from level 1 to 5 for males and females with increasing score representing higher climbing ability. It is our recommendation that the two tables presented here be adopted in climbing research for reporting climbing abilities in future studies.

#### 4. A comparison grading scale for reporting climbing ability

A particular problem for climbing research resulting from the mixed number and letters systems used in many grading systems (for example USA, British technical and French/Sport) occurs with any statistical analysis that involves grades using these systems. To get around these problems researchers have developed their own study scales using numbers only and converted actual climbing grades to their study scale. The first to do this was Watts et al. [45] and so this scale has been

added to the comparison tables for males and females. Other who have created such scales include Schweizer et al. [46] who developed a scale from 1–24, Padrenosso et al. [47] with a scale from 0.75–5.25, Llewellyn and Sanchez [48] with scale from 1–16, Michailov et al. [7] who used a scale from 2.50 to 5.50, and Draper et al. [42] whose scale was from 1–14. In addition, Schöffel et al. [49] in a publication for the International Mountaineering and Climbing Federation (UIAA) recently published a metric version of the UIAA grading scale (ranging from 5.66 to 12.00) and this has been included in Table 1 and 2 for comparative purposes.

Not only are there a wide range of grading scales for rating actual climbs around the world (a number of which are shown in Tables 1 and 2), but on top of this researchers have developed a whole series of their own study scales. Clearly, given the need to complete statistical analyses of research data, it is necessary to have a number only grading scale for climbing studies,

but the inconsistencies between studies make comparison between studies even more problematic. A sensible approach to avoiding this problem was adopted by España-Romero et al. [50] who completed their analysis using the already existing scale created by Watts et al. [45]. Perhaps an even simpler solution though, has been missed by researchers to date and that would be to use the Ewbank system. Not only is this grading system used in three popular climbing destinations, but it is an existing climbing scale that is based on numbers only and as such would be ideal for statistical analysis. It would therefore be our recommendation that all future studies conduct their statistical analyses using either the Watts et al. [45] scale as the original researcher based system or the Ewbank system as a whole number climbing grading scale.

## 5. Areas for future research

The aim of this paper was to suggest a number of points that might be considered by researchers presenting findings for rock climbing studies in the future. With regard to future research there are a large number of studies that could be conducted to improve our understanding of the sport. Rock climbing is a multifaceted sport with a number of major disciplines each of which require further investigation to examine the similarities and differences between other forms of climbing. To date, the majority of papers presented have focused on sport climbing and used top-roping, perhaps for safety reasons, to protect the climbers during ascent. Research by Hodgson et al. [51] and Draper et al. [42] provided evidence that there are significant psychological and physiological differences between lead climbing and top-roping. As a consequence, it would be useful for future studies to further examine the differences between lead climbing and top-roping and to investigate lead climbing and the specific demands it places on the climber. Furthermore, the majority of studies published to date have reported findings based on research conducted on indoor artificial climbing walls. Accordingly, the differences between indoor and outdoor climbing along with research to improve our understanding of the psychophysiological and environmental effects of climbing outdoors on natural rock merit further investigation.

With regard to improving performance, a notable concern for many climbers and particularly competition climbers, Goddard and Neumann [52] identified six key factors that impact upon the development of a

Table 3  
Factors that affect climbing performance

Physical fitness
External conditions
Co-ordination and technique
Psychological aspects
Background conditions
Tactical aspects

N.B. Adapted from Goddard and Neumann 1993, p. 12.

climber's ability. The factors are shown in Table 3 and each requires further investigation to improve our understanding both of the demands of climbing and also the best methods for improving performance in each aspect.

With regard to the key physical fitness components for climbing, these were summarised in a table by Draper et al. [42]. The key aspects, agreed upon by many leading climbers and coaches include strength, power, power endurance and flexibility. To monitor improvements in fitness sport specific measures of these aspects of fitness are required for climbing. To date researchers have identified sport specific tests of strength, power and flexibility [14,42,53,54]. Further research could also usefully address the measurement of power endurance and the development of a sport specific test of this aspect of climbing fitness. The completion of this research would mean that it was then possible to measure each of the key components of fitness for climbing.

The aim of this paper was to make suggestions about reporting climber characteristics, scales to use for statistical analysis and to provide gender specific tables that can be used to classify climber ability groups. Within the methods section future research studies could usefully report age, height, mass, body fat percentage, aerobic capacity, climbing ability, years of experience in climbing, days and hours of training per week and the main disciplines pursued. It would be our recommendation also that for statistical purposes, where necessary, researchers use either the Watts et al. [45] or Ewbank grading scales with which to make comparison between studies easier in future. Finally we suggest that Tables 1 and 2 from this paper could be used to classify climber groups in future research papers.

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**Appendix H** Pilot Study Four: Draper, N., Dickson, T., Blackwell, G., Fryer, S., Priestley, S., Winter, D., Ellis, G. (2011). Self-reported ability assessment in rock climbing. *Journal of sports sciences*, 29 (8), 1-8

<http://dx.doi.org/10.1080/02640414.2011.565362>

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**Appendix I** Pilot Study Five: Dickson, T., Fryer, S., Draper, N., Winter, D., Ellis, G. Hamlin, M. (2012) Comparison of plasma cortisol sampling sites for rock climbing. *Journal of Sports Medicine and Physical Fitness*. 52, **688-695**

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## Appendix JCo-Authorship Forms

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DRAPER, N., DICKSON, T., FRYER, S., BLACKWELL, G., WINTER, D., SCARROTT, C. & ELLIS, G. 2011. Plasma cortisol concentrations and perceived anxiety in response to on-sight rock climbing. *International journal of sports medicine*, 33, 13-17.

Please detail the nature and extent (%) of contribution by the candidate:

Design of the study

Participant recruitment and data collection

Cortisol assay

Data analysis and interpretation (compiling data set)

Overall: 65%

#### Certification by Co-authors:

If there is more than one co-author then a single co-author can sign on behalf of all

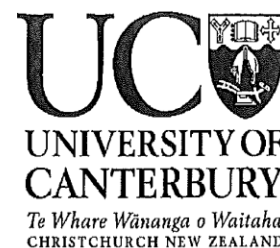
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Name: <i>Simon Fryer</i>	Signature:	Date: <i>24/6/2013</i>



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Please detail the nature and extent (%) of contribution by the candidate:

Methodological design and implementation

Overall: 35%

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*Chapter 5 and Chapter 6*

DICKSON, T., FRYER, S., BLACKWELL, G., DRAPER, N. & STONER, L. 2012. Effect of style of ascent on the psychophysiological demands of rock climbing in elite level climbers. *Sports Technology*, 1-9.

Please detail the nature and extent (%) of contribution by the candidate:

Design of the study

Participant recruitment and data collection

Cortisol assay and analysis

Data analysis and interpretation (compiling data set)

Statistical analysis




Overall: 50%

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*Chapter 5 and Chapter 6*

FRYER, S., DICKSON, T., DRAPER, N., BLACKWELL, G. & HILLIER, S. 2012. A psychophysiological comparison of on-sight lead and top rope ascents in advanced rock climbers. *Scandinavian Journal of Medicine & Science in Sports*.

Please detail the nature and extent (%) of contribution by the candidate:

Design of the study

Participant recruitment and data collection

Cortisol assay and analysis

Data analysis and interpretation (compiling data set)

Wrote the paper




Overall: 75%

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*Chapter 5 Section 5.5.2 and 5.6*

DICKSON, T., FRYER, S., DRAPER, N., WINTER, D., ELLIS, G. & HAMLIN, M. 2012. Comparison of plasma cortisol sampling sites for rock climbing. *The Journal of sports medicine and physical fitness*, 52, 688-688.

Please detail the nature and extent (%) of contribution by the candidate:

Design of the study

Participant recruitment and data collection

Cortisol assay analysis

Overall: 50%

### Certification by Co-authors:

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*Chapter 5, Section 5.5.2 Blood Sampling*

FRYER, S., DRAPER, N., DICKSON, T., BLACKWELL, G., WINTER, D. & ELLIS, G. 2011.  
Comparison of lactate sampling sites for rock climbing. *International journal of sports medicine*, 32, 428-432.

Please detail the nature and extent (%) of contribution by the candidate:

Design of the study

Participant recruitment and data collection

Wrote the paper




Overall: 75%

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